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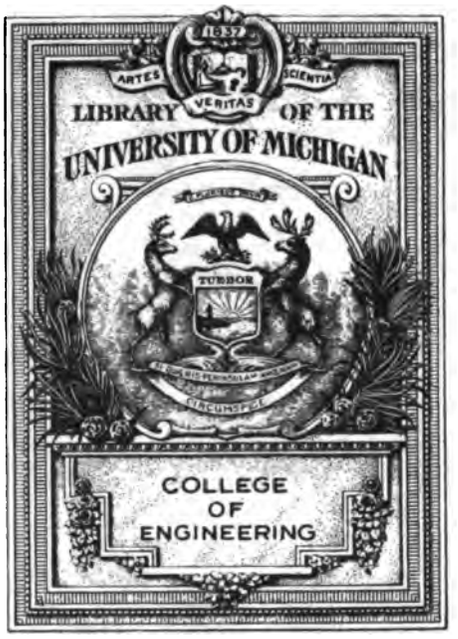

THE GIFT OF
New York State Bridge and
Tunnel Commission

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CEREMONY OF BREAKING GROUND FOR THE VEHICULAR TUNNEL, COLUMBUS DAY, OCTOBER 12, 1920

Left to right: Mayor Frank Hague of Jersey City, N. J., Lieut.-Gov. Harry C. Walker of New York (swinging pick), Mayor John F. Hylan of New York City, Chairman Weller H. Noyes of the New Jersey Commission, General George R. Dyer, Chairman of the New York Commission, Governor Edward I. Edwards of New Jersey (holding shovel), Commissioner John F. Boyle of the New Jersey Commission and Commissioner E. W. Bloomingdale of the New York Commission.

Legislative Document (1921) No. 64

STATE OF NEW YORK

REPORT

OF THE

New York State Bridge and Tunnel Commission

TO THE

Governor and Legislature of the State of New York

1921

GEN. GEORGE R. DYER
Chairman
E. W. BLOOMINGDALE
McDOUGALL HAWKES
A. J. SHAMBERG
GROVER A. WHALEN
FRANK M. WILLIAMS
Commissioners

CLIFFORD M. HOLLAND
Chief Engineer
PAUL WINDELS
Counsel

MORRIS M. FROHLICH
Secretary

TRANSMITTED TO THE GOVERNOR AND LEGISLATURE, MARCH 21, 1921

ALBANY
J. B. LYON COMPANY, PRINTERS
1921

REPORT

March 21, 1921.

To the Honorable President of the Senate, Session of the Legislature 1921, Albany, New York:

SIR.— I have the honor to transmit herewith the Report of the New York State Bridge and Tunnel Commission, dated March 21, 1921.

Respectfully yours,

GEORGE R. DYER,
Chairman.

391580

NEW YORK STATE BRIDGE AND TUNNEL COMMISSION
ANNUAL REPORT

Dated, *March* 15, 1921.

To the Honorable The Governor and the Legislature of the State New York:

GENTLEMEN:— The New York State Bridge and Tunnel Commission has the honor to present to you the following report.

This Commission was authorized by Chapter 178 of the Laws of 1919 (signed by the Governor, April 10, 1919) to proceed with the construction, in co-operation with the State of New Jersey, of a tunnel or tunnels between a point in the vicinity of Canal street on the island of Manhattan, State of New York, and a point in Jersey City in the State of New Jersey, for the exclusive use of pedestrians and of vehicles not operated by public service corporations. Similar action was taken at that time by the Legislature of the State of New Jersey which gave like authority to the New Jersey Interstate Bridge and Tunnel Commission to join with this Commission in the undertaking.

REPORT OF 1920

On February 10, 1920, the undersigned had the honor to transmit to the Governor and the Legislature, its report, stating in detail what had been accomplished by it from the time of the organization of the Commission under Chapter 178 of the Laws of 1919 to the date thereof. The report among other things referred to the selection of the chief engineer, the board of consulting engineers and the engineering staff, and contained the treaty entered into between the States of New York and New Jersey acting by the respective commissions wherein were provided the terms and conditions upon which the construction of the vehicular tunnel was to be undertaken by the States. The report also contained, as an appendix, a report of the chief engineer to the Commission dated December 30, 1919, in which he analyzed the various engineering problems with which the Commission was confronted, and a statement of the conclusions and results of his investigations and studies. These conclusions were approved by the consulting board. In that report the chief engineer stated that twin, cast-iron tubes, with an external diameter of twenty-nine (29) feet, providing a twenty foot roadway to accommodate two lines of vehicular traffic in each direction, and a two foot sidewalk, would be the type of tunnel best suited to the immediate needs of vehicular and pedestrian traffic between the States at the present time, and the type most certain of successful construction.

PUBLIC HEARINGS

Following the transmission of the last report the Commission has continued its studies as to the best type of tunnel and the most practicable method of construction. Public meetings were authorized to be held to which were invited all persons who believed they had valuable ideas to suggest relative to the problems of the Commission. The hearings were held in New York City in the State of New York, and in the cities of Newark and Jersey City in the State of New Jersey. They were largely attended and aroused a great deal of public interest. All suggestions submitted, either orally or in written briefs, were carefully considered by the Commission, the chief engineer and the board of consulting engineers.

CONTRACT NO. 1 AWARDED

Thereafter and on September 27, 1920 Contract No. 1 for the construction of the land shafts in the borough of Manhattan was awarded to Holbrook, Cabot & Rollins Corporation, the lowest bidder therefor, and on October 12, 1920, the work of actual physical construction of the tunnel was formally commenced by the breaking of ground on the site of the location of the southerly shaft in the city park at Canal and West streets, New York city. This event was marked by formal ceremonies, participated in by distinguished guests representing the nation, State and city and witnessed by many thousands of people. The work under Contract No. 1 is progressing satisfactorily and according to schedule requirements.

CONTRACT NO. 2 ADVERTISED

The construction of the land shafts in the State of New Jersey has been delayed somewhat by reason of the necessity for making satisfactory arrangements with the Erie Railroad Company in and near whose railroad yard in Jersey City the exit, entrance and ventilating shafts of the tunnels will be located. They have reached such a stage at this time that the commissions have felt fully warranted in authorizing the advertising of requests for sealed proposals for work under Contract No. 2 covering the construction of the secondary shafts in Jersey City. If negotiations with the Erie Railroad are completed it is expected that proposals will be opened on March 29th and the contract awarded immediately thereafter and that the actual physical commencement of work in New Jersey will occur on Saturday, April 16, 1921.

This event will also be marked by formal ceremonies. The Mayor of Jersey City has announced his intention to declare the day a public holiday in that city as an evidence of the great popular interest in New Jersey in this undertaking. It is expected that the occasion will be made notable by the presence of the Governors and United States Senators of the respective states, the Mayors of the cities and other distinguished people.

CONSTRUCTION PROGRAM

The schedule of the chief engineer contemplates the completion of construction of the tunnels on December 31, 1924. To carry out the schedule certain

important elements are necessary, not the least of which is the ability of the commissions to award contracts promptly as the work develops, so as to keep the various portions of the work of construction progressing rapidly and in proper co-ordination.

The Commission realizes the tremendous demands which are being made upon the treasury of the State and the great difficulties confronting the Governor and the Legislature in meeting such of them as are imperative. It is also aware of the fact that the Governor and Legislature fully appreciate the importance of the tunnel project, and the necessity of finishing it promptly, not only to furnish the long needed and long sought for relief to the people of the two states, but also to advance as quickly as possible the date when the tunnel will be in successful operation and producing an income. The Commission is mindful of the fact that the longer the period of construction is prolonged, whether by reason of lack of financial resources or otherwise, the greater the overhead and the interest charge on the capital investment during the period of construction and therefore the greater the cost of the tunnel, and the greater the loss through the deferred date of the opening of the tunnels and the consequent receipt of revenue from its operation. Anything which is done to disturb or delay the progress of work even for one day results in a financial loss, not only to the State of New York, but also to the State of New Jersey, our partner in this enterprise. The undersigned believes the Governor and the Legislature appreciate the importance of making such provision for the needs of the Commission and extending such assistance to it as will enable it to avoid every delay and push the construction of the tunnel to prompt and successful completion.

NEW JERSEY'S SHARE OF COST PROVIDED

In this connection we refer to the action taken by the Legislature of the State of New Jersey last year authorizing a popular referendum on a proposed issue of $28,000,000.00 of bonds of the State to finance the completion of the construction of the vehicular tunnel and the construction of a bridge over the Delaware River between Camden, N. J. and Philadelphia, Pa. The bond issue was approved by an overwhelming vote, approximately 569,300 votes for it and 94,797 votes against it, thus indicating the popularity of the vehicular tunnel project in the State of New Jersey and the approval by the people of that State, of the conclusions reached by the commissions as to the best type of tunnel and most practical method of construction. Our conclusions had been given great publicity in the State of New Jersey by Chambers of Commerce and other civic organizations and were important issues in the campaign on the referendum. There is thus immediately available New Jersey's one-half of the cost of the tunnel project.

PROVISION FOR NEW YORK'S SHARE OF COST

The New York Commission has heretofore received from the legislature two million dollars. It has estimated its needs for the fiscal year expiring on June 30, 1922 at eight and one-half million dollars. It stated however, that if the appro-

priation instead of being included in the budget, thus having to cover the period indicated, would be made immediately available by a special act and similar action taken in January, 1922 the Commission could at this time carry on the work without delay with a substantially smaller sum of money. For that reason an act has been proposed by the chairmen of the Senate Finance Committee and the Assembly Ways and Means Committee making immediately available to the Commission the sum of five million dollars. This sum will be adequate for the Commission's needs until the next session of the legislature.

ERIE RAILROAD NEGOTIATIONS

One of the most difficult problems with which the Commission had to deal during the past year relates to the acquirement of property and property rights or easements in the Erie Railroad yards in Jersey City.

It so happens that the provisions of the New York Statute require the location of the New York entrance and exit of the tunnels in the vicinity of Canal Street, in the Borough of Manhattan, which in turn makes it necessary to construct the tunnels including the ventilating shafts and a portion of the open cut work in the Erie Railroad yard and to locate the entrance and exit of the tunnels just outside its boundary line.

This railroad yard serves as the terminus of a great railroad system. The officials of the company claim that it is already cramped and inadequate to the needs of this system and that every square foot of space in it is needed to avoid interference of traffic. The yard is a net work of railroad tracks and apparently in order to meet the needs of the great system which it serves, it must be used and operated as intensively as possible and with the highest grade of technical railroad skill.

The situation of the railroad therefore had to be studied with great care so that the construction of the tunnels should result in just as little interference as possible with the railroad traffic in the yard, and the tunnel alignment and location of the shafts had to be provided for in such manner as to require as little of the railroad company's property as possible consistent with the proper construction of the tunnels. The commissions felt that the best way to proceed would be to work, if possible, in harmony with the officials of the Erie Railroad Company in the formulation of a plan which would be the result of the best judgment of the engineers and administrative officials of the Railroad Company and the engineers and members of the Commission. For that purpose the Erie Railroad Company appointed a small committee to meet with a similar committee representing the New York and New Jersey Commissions.

The Committees commenced their discussions in July, 1920, and carried them on to December of that year. Meetings were held at frequent intervals, maps of the railroad yard studied with great care and various plans considered. On December 9, 1920, the commissions made an offer to the Erie Railroad Company, which offer after further negotiations was accepted by the company on December 30, 1920, subject to the approval of the parties to the form of contract

and the working out of minor details. The undersigned feels that the general plan which is under discussion is eminently fair to both sides and secures without delay or uncertainty the rights which the commissions need to proceed promptly with the construction of the tunnels. A special committee representing both sides is now carefully studying the form of the contract which we have every reason to believe will be signed this month, (providing no unexpected obstacle intervenes), thus terminating, in a way entirely satisfactory to the New York and New Jersey Commissions, this very difficult negotiation.

PROBLEM OF VENTILATION

Another important problem which the Commission must solve relates to the adequate ventilation of the tunnels. The Commission during the past year has continued and completed investigations under the immediate direction of the United States Bureau of Mines, to determine the composition of exhaust gases of motor vehicles and the physiological effects of such exhaust gases on the human body. The purpose of these investigations was to discover what will be the condition of the air in the tunnel as a result of the operation through it of a continuous and rapidly moving line of motor vehicles and also what effect that air will have upon persons using the tunnel. On the basis of exact information on these points will be determined the best method of ventilating the tunnels, the rapidity with which the air will have to be changed to provide adequate ventilation, and the size of the plant and the amount of power needed for that purpose. The data which we sought to obtain through the Bureau of Mines had never theretofore been scientifically and thoroughly prepared.

It was imperative that the Commission have the information without delay because the design of the tunnels and the amount of space needed for ventilating purposes were directly related to it. For that reason the Commission sought the best medium for the purpose of conducting the investigations. It made strenuous efforts to have Congress appropriate moneys sufficient therefor, even going so far as having appropriations proposed on the floor of the House of Representatives in the form of an amendment to the Appropriation Bill but it was not successful. The information has now been accumulated. It is of the utmost scientific value and has been very much sought for throughout the country. As a result of it the Commission and its engineers are completely satisfied that the tunnels can be thoroughly and adequately ventilated and made safe and comfortable for continuous use.

Further investigations are being conducted by the Bureau of Mines in conjunction with the University of Illinois for the purpose of determining some questions relating to the type and size of the ventilating ducts and equipment. These investigations are being made at the Engineering Experiment Station of the University at Urbana, Ill. and in the experimental coal mine of the Bureau of Mines at Pittsburgh, Pa. To direct the investigations at Urbana the Commission has secured the services of Professor A. C. Willard of the University who is con-

sidered to be one of the foremost authorities in this particular field of scientific research. It has also been very fortunate procuring for these investigations financial assistance from the Federal Government in that the Bureau of Mines has contracted to make a contribution to the cost thereof in the use of plant, equipment and services of the value of $25,000.00 and this contribution has resulted in the direct saving of that amount of money to the two States. It is expected that before May 1, 1921, there will be available all the data which the Commission's engineers will need relating to the problem of ventilation, and the final designs of the tunnel can then be made. This is important because the schedule of contracts calls for an award of Contract No. 3 (the first contract for the river portion of the tunnels) by July 1, 1921.

INSPECTION OF MATERIALS

The Commission is engaged in negotiations with the Transit Construction Commissioner of the City of New York for the purpose of arranging for the use of the inspection staff of the Transit Construction Commissioner for the inspection of steel, cast iron, cement and such other materials as will enter into the construction of the tunnels. The purpose of this arrangement is to save money and to secure the immediate services of an experienced and competent inspecting staff. The staff is now being paid by the Transit Construction Commissioner. Owing to a temporary lull in New York City subway construction, its full time is not being used. The commissions could not at this time make full use of an inspecting staff and therefore the creation of one at the present time would result in a very heavy overhead. For that reason the New York and New Jersey Commissions are proposing to join with the Transit Construction Commissioner in the use of his inspecting staff, prorating the payroll and overhead on the basis of time actually used by the commissions. An agreement as to terms has been reached and it is expected that the contracts will be formally executed very shortly. This is a most advantageous arrangement for the commissions. It is expected that as the work develops it will be possible to substitute for the inspectors of the Transit Construction Commissioner such inspectors of materials as may be available in the office of the State Engineer and Surveyor.

ACQUISITION OF LAND IN NEW YORK CITY

The Commission is also engaged in negotiations with the Commissioners of the Sinking Fund of the City of New York in an effort to procure, without cost to the Commission, the property needed on Canal, Washington and Spring Streets, New York City, for the construction of the ventilation shafts and for all underground easements required from the city for the construction of the tunnels, particularly where the tunnels cross the beds of public streets, and the city's property between the bulkhead and pierhead lines. The Commission is very hopeful for a successful conclusion of these efforts which will result in a saving of a very substantial sum of money to the State of New York.

AERIAL VIEW, SHOWING SITE OF CONTRACT NO. 1 — VEHICULAR TUNNEL — CANAL, SPRING AND WEST STREETS, NEW YORK CITY

The survey of real property required for the construction of the tunnels in the State of New York has been completed. The engineers are preparing the descriptions, a contract has been made with the New York Title and Mortgage Company for a complete chain of title for the past one hundred years and a report of all encumbrances of record with respect to each of the parcels. The examination of titles is being conducted under the direction of the Attorney General, and it is expected that the Commission will acquire all real property in New York City by entry and appropriation, during the course of the next half year.

During the past year the Commission received information indicating that certain persons were arousing fears in the minds of owners and tenants of property immediately adjacent to the tunnel site on the New York side as to the nature of the condemnation proceedings and the result thereof to the said persons. Their purpose was to secure retainers of professional services in condemnation proceedings. For the protection of the owners and tenants and for their information the Commission sent to all such persons in the neighborhood of the tunnel site, an informal statement outlining the provisions of Chapter 178 of the Laws of 1919 pursuant to which the real property is to be acquired, so that accurate information should be in the possession of all such persons.

REQUESTS FOR OTHER INVESTIGATIONS

On March 2, 1920 a resolution was adopted by the Senate and Assembly directing the Commission to investigate and report on the practicability of the construction of a bridge or tunnel between Staten Island in the City and State of New York and a point in the State of New Jersey. Such an investigation would require the expenditure of a substantial sum of money. The resolution made no provision for an appropriation for the purpose thereof. The Attorney-General of the State of New York advised the Commission that it had no authority to use the funds placed at its disposal under Chapter 178 of the Laws of 1919 for the purpose of the resolution and that such funds could not be used for any purpose other than provided for in said Chapter 178 of the Laws of 1919. For this reason the Legislature was forthwith advised that the Commission could not proceed with the investigation unless an appropriation for that specific purpose was made. Such action was not taken by the legislature and for that reason the investigation was not carried on.

ORGANIZATION

On June 15, 1920 the commissions appointed Col. George L. Watson a member of the Consulting Board to take the place of the late Col. Henry W. Hodge. Colonel Watson is a resident of the State of New Jersey. On November 9, 1920, Hon. Lewis F. Pilcher, State Architect, was appointed Consulting Architect to the Commission, to serve without compensation, and on November 23d James L. Wells, formerly Treasurer of the State of New York, and a gentleman of great experience and knowledge of real estate values in the City of New York,

was appointed real estate appraiser to the Commission to serve in connection with the acquirement of real property in the State of New York as provided in Chapter 178 of the Laws of 1919. The Commission is fortunate in being able to secure as appraiser the services of a gentleman of Mr. Wells' high standing and great experience and the terms of compensation proposed by Mr. Wells were extremely modest.

REPORT OF CHIEF ENGINEER

The results of the various studies and investigations of the Commission are contained in the report of the chief engineer, dated December 31, 1920 which is annexed hereto and submitted herewith as approved March 8, 1921 by the Board of Consulting Engineers. Mr. Holland's report contains a mass of valuable engineering information, much of which is original and of great interest to the engineering profession throughout the country. At least six of the largest cities in the United States are about to undertake the construction of vehicular traffic tunnels and are making use of the results of the pioneer work which has been done by this Commission and its engineering staff.

Owing to the absence of Commissioner Hawkes, who is now in Europe, it has not been possible to submit this report to him.

Respectfully submitted,

New York State Bridge and Tunnel Commission.

GEORGE R. DYER,
Chairman.

E. W. BLOOMINGDALE,
A. J. SHAMBERG,
FRANK M. WILLIAMS,
GROVER A. WHALEN.

MORRIS M. FROHLICH,
Secretary.

AERIAL VIEW, SHOWING LINE OF THE VEHICULAR TUNNEL AT MANHATTAN SHORE

NEW YORK STATE BRIDGE AND TUNNEL COMMISSION AND NEW JERSEY INTERSTATE BRIDGE AND TUNNEL COMMISSION

REPORT OF C. M. HOLLAND — CHIEF ENGINEER

December 31, 1920

New York State Bridge and Tunnel Commission and New Jersey Interstate Bridge and Tunnel Commission.

GENTLEMEN.— I submit herewith my report for the year ending December 31, 1920, which completes a period of eighteen months since the commencement of the work on the plans for the vehicular tunnel. The first six months were spent in making studies of the plan, type, and size of tunnel. This comprised a general survey of tunnel location, traffic, methods of construction and ventilation, estimates of cost, and survey. As a result of these investigations, definite plans for carrying on the work were recommended at the close of the year 1919.

During the year 1920 detail studies have been continued and work has been steadily in progress on the preparation of contracts, plans, and specifications which have closely followed the preliminary work. The first contract providing for the construction of two shafts in New York City was advertised on August 24, 1920, and started on October 12th. The contract, plans, and specifications are completed for starting similar work in Jersey City but construction has not been begun as the negotiations with the Erie Railroad Company for the necessary rights and easements for constructing the tunnel through its property have not been completed.

In the planning of a public undertaking of the magnitude of the Hudson River Vehicular Tunnel it is necessary that broad consideration be given to many features besides those of actual tunnel building. The building of the tunnel structure itself is a great engineering problem, but many investigations beyond the technical design have been required. The best location and arrangement of tunnel roadways has made necessary a complete survey of present and future traffic and of the influence of the tunnel upon the development of the contiguous territory. Traffic conditions have been considered from many angles, including congestion of the tunnel roadway, adequate approaches, congestion in the adjacent streets, tunnel grades, width of roadway, capacity, the growth and development of vehicular traffic, and many other important features, so that the tunnel, when completed, will render the greatest service to the public.

Many different schemes for constructing the tunnel have been under consideration. At the public hearings in New York City, Newark, and Jersey City, the discussion of methods of tunnel construction other than the one recommended in the 1919 report largely centered upon the forty-two foot concrete block tunnel which had been rejected and though every opportunity was afforded to set forth the advantages of this tunnel, the conclusion reached was not changed. The discussion of the trench tunnel resolved itself into the question of dredging and maintaining an open trench under the Hudson River. All of the different schemes were given most careful consideration not only at the public hearings but also at conferences in the offices of the Commissions between its engineers and the proponents of each method of construction, but after very careful study, none are recommended for adoption largely because they are either untried and undeveloped or are not adapted to meet successfully Hudson River conditions. The investigations of these plans has consumed a large part of the time of the Commissions' engineers throughout the year.

The plan for the prosecution of the work has been carefully worked out with a view to developing the project so that it will be rapidly advanced and economically carried forward as the necessary funds are made available. The construction program provides for letting the work in a number of different contracts. This will not only reduce interest charges during construction but it is also expected that it will make possible the taking advantage of any reduction in prices during the next few years. Accordingly, the first contracts to be let are those for the shafts on either side of the river from which tunneling operations can be started; next will follow the major portion of the work, that of constructing the river tunnel; and finally, the approaches, the construction of which is independent of the under-river portion.

In planning the vehicular tunnel which is essentially an engineering problem it is fully appreciated that the various controlling demands of the engineering design should receive architectural treatment in keeping with a great public work connecting the States of New York and New Jersey. The architectural treatment of the approaches and of dependent structures has been under discussion with the Consulting Architect and will be developed as the work progresses. Numerous conferences have been held throughout the year with the various State and City Departments, private corporations, and individuals who are either directly interested or will be affected by the plans as ultimately carried out.

The further study of conditions in Jersey City has resulted in a modification of the plan for a plaza by the substitution of two half-blocks (Plate No. 1) instead of one entire block as at first proposed. This modification will be made possible by the agreement on the part of Jersey City to the closing of Eleventh Street, which with the widening of Twelfth Street to 100 feet will solve a most difficult traffic problem. The streets in Jersey City in the vicinity of the tunnel are thirty feet wide between curbs and under existing street conditions the only arrangement whereby traffic could reach the tunnel as originally planned was through a plaza occupying the entire block between Eleventh and Twelfth Streets, but this was not as satisfactory, due to the inadequacy of these streets. This modification insures a better approach for traffic entering the tunnel and will conform more nearly with the plans for approaches to the tunnel from Jersey City Heights.

The location of the tunnel under the Erie Railroad yard has been modified as a result of the negotiations with that company to conform with its plans for future development. This has required the moving of the tunnel slightly south so that its location will harmonize with the plans for new pier construction, and the method of conducting the work within the yard has been modified so as to interfere as little as possible with railroad operation. The proposed agreement with the Erie Railroad Company provides for all the rights and easements necessary for the construction, operation, and maintenance of the tunnel, including the sinking of two shafts within the railroad yard, the construction of a ventilation building in connection with these shafts, the construction of two shafts near the pierhead line and the erection overhead of a ventilation building, and the construction of the tunnels by the shield method from the pierhead line west to a point where the method of construction changes from tunneling to open cut excavation. The Erie Railroad Company is to build and maintain a pier which will serve as a protection to the tunnel and shafts. In addition to the rights and easements which are to be obtained from the Erie Railroad Company, negotiations are now in progress with the Delaware, Lackawanna and Western Railroad Company for the right to construct and operate the portion of the tunnel which lies under its property. The plans for the construction have been discussed with the Chief Engineer of that Company preliminary to negotiations which have been delayed, pending the conclusion of the agreement with the Erie Railroad Company.

In New York, the waterfront is owned by the municipality and the location of the tunnel has been made to conform with the plans of the Department of Docks for the improvement of the Hudson River waterfront, so that the tunnel will be located under a modern pier harmonizing with the proposed development of the waterfront, Plates Nos. 6 and 7. The ventilation equipment building for the New York land shafts is to be located on the west side of Washington Street between Canal and Spring Streets on property now owned by the city, Plate No. 8. The plans

for the tunnel exit require a modification in the width of street and sidewalk conditions on the south side of Canal Street, and application has been made to the Board of Estimate and Apportionment of the City of New York for its approval of this change, (Plate No. 5).

TRAFFIC

In the 1919 Report, the volume of traffic which would use the tunnel was estimated from the records of the ferry companies, the three-day counts made during the summer and fall of 1919, and a study of traffic over the East River bridges. Supplementing last year's studies, traffic counts of vehicles crossing the Hudson River ferries were made during the late summer and fall of 1920. These counts were made not only to obtain the volume of traffic but also to ascertain its character and, in connection with data obtained in previous years, to furnish some idea of the growth of the different kinds of traffic.

In summarizing and classifying the data, the grouping of the ferries is the same as was adopted in 1919. The first group consists of the five ferries nearest the tunnel which, as was observed in 1919, carried about one-half of the total traffic. This group is referred to as the " Five-Ferry Group "; namely,

Ferry	New Jersey Terminal	New York Terminal
Pennsylvania Railroad	Exchange Place	Desbrosses Street
Pennsylvania Railroad	Exchange Place	Cortlandt Street
Erie Railroad	Pavonia Avenue	Chambers Street
D. L. & W. Railroad	Hoboken	Barclay Street
D. L. & W. Railroad	Hoboken	Christopher Street

The second group, referred to as the " Six-Ferry Group," includes all other ferries south of Forty-second Street; namely,

Ferry	New Jersey Terminal	New York Terminal
Central Railroad of New Jersey	Communipaw	Liberty Street
Central Railroad of New Jersey	Communipaw	West 23d Street
Erie Railroad	Pavonia Avenue	West 23d Street
D. L. & W. Railroad	Hoboken	West 23d Street
D. L. & W. Railroad	14th Street, Hoboken	West 23d Street
West Shore Railroad	Weehawken	Cortlandt Street

The third group, referred to as the " Four-Ferry Group," includes all the ferries at Forty-second Street and to the north. They are so far away from the tunnel that, while some traffic may be diverted from them, none has been included in estimating tunnel traffic.

It has been found that traffic varies from day to day so that the average for three consecutive days may not be truly representative of the average monthly traffic. Further, there is a considerable difference in the monthly traffic crossing the ferries which, in general, is less in the winter than in the summer. As a check upon the three-day counts, data have been obtained for the year 1920 from the records of the ferries as to the volume of traffic throughout the entire year and it is found that the three-day counts cannot be extended to represent correctly traffic during the entire year, even with seasonal corrections. Accordingly, the yearly traffic and the average week day traffic is based upon the data obtained from the ferry companies and the three-day counts are used as an indication of the hourly distribution of traffic, its character, the waiting list at different hours of the day, and its source.

This year's increase in vehicular traffic crossing the Hudson River is slightly less than the increase estimated in 1919. The decline in the movement of traffic across the Hudson River has not been confined to the ferries alone, for there has been a very appreciable reduction in the amount of lighterage due to the general slump in business.

The following tables show the growth of traffic for the different ferry groups:

FIVE-FERRY GROUP

YEAR	Total annual traffic from date obtained from railroad companies	Daily average week-day traffic				Total	Per cent of Increase
		Horse drawn		Motor driven			
		Number	Per cent of Total	Number	Per cent of Total		
1914	2,839,055	7,655	86.9	1,159	13.1	8,814	
1915	2,811,249	7,137	82.7	1,497	17.3	8,634	2.0
1916	3,042,756	7,218	78.0	2,038	22.0	9,256	7.1
1917	3,279,019	6,785	68.7	3,093	31.3	9,878	6.9
1918	3,496,620	6,270	59.9	4,193	40.1	10,463	5.8
1919	3,731,032	5,693	50.9	5,404	49.1	11,177	6.8
1920	3,853,793	4,994	43.4	6,509	56.6	11,503	2.9
SIX-FERRY GROUP							
1914	2,089,311	5,346	81.2	1,233	18.8	6,579	
1915	2,090,519	4,936	75.1	1,636	24.9	6,572	0.0
1916	2,256,601	4,875	69.1	2,184	30.9	7,059	7.3
1917	2,430,893	4,755	62.5	2,855	37.5	7,610	7.8
1918	2,669,003	4,594	55.1	3,739	44.9	8,333	9.5
1919	2,646,042	3,884	47.3	4,344	52.7	8,228	—1.3
1920	2,361,727	2,972	42.0	4,099	58.0	7,071	—14.0
FOUR-FERRY GROUP							
1919	2,036,421	.....	.....	.....	.....	5,224	
1920	2,089,035	.....	.....	.....	.....	5,400	3.3

From the preceding tables, it is to be noted that the increase in motor driven vehicles and the decrease in horse drawn vehicles has continued during the year 1920 at approximately the same rate as during the year 1919. The average week day traffic crossing the ferries during 1920 amounts to 23,974 vehicles daily.

CAPACITY OF ROADWAYS

In the 1919 Report two twenty foot roadways, each providing for two lines of traffic, were recommended as best suited to meet traffic requirements across the Hudson River between Canal Street, Manhattan, and Twelfth Street, Jersey City. During the year, the investigations of roadway capacities have been continued and a particularly favorable opportunity was presented to study the capacities of the different roadways of the East River Bridges at the time of the Brooklyn Rapid Transit strike during the latter part of August and the early part of September when the volume of vehicular traffic was far above the normal. The conditions under which traffic moves over these bridges are comparable with those of the tunnel as the approach grades of $3\frac{1}{2}\%$ correspond with the maximum tunnel grades. Counts were made of the traffic over the Williamsburg, Manhattan, and Brooklyn Bridges, which under maximum conditions are operated practically as two, three, and one-line roadways, respectively. The movement of traffic over the roadways of the Williamsburg Bridge, which are nearly the same width as the tunnel roadways, was of particular interest. The increased traffic did not give all the data that was anticipated as the changing of traffic conditions for short periods did not permit of regulations becoming effective so as to get the traffic into the best order. The same delays which occurred in the traffic approaching the Williamsburg Bridge under

ordinary conditions were much more apparent with the increase in traffic and produced greater congestion at the approaches.

The counts made of vehicles over the Williamsburg Bridge for short periods are given herewith:

MAXIMUM TRAFFIC OBSERVATIONS ON WILLIAMSBURG BRIDGE, SOUTH ROADWAY — AUGUST 30, 1920, P. M.

Time Interval	Maximum Traffic Observed	Rate per Hour	Remarks
1 minute	36	2,160	Both roadways used for east-bound
2 minutes	59	1,770	traffic at time of count.
3 minutes	87	1,740	Composition of traffic:
5 minutes	127	1,524	Pleasure and light commercial
10 minutes	245	1,470	cars 36%
15 minutes	338	1,352	Motor trucks 48%
30 minutes	571	1,142	Horse trucks 16%
60 minutes	1,021	1,021	100%

The fast line was given over wholly to motor vehicles and the slow line to horse drawn trucks and the slower motor vehicles. Capacity conditions extended over a period of one, two, three, five, and even up to ten consecutive minutes, the latter extending over a sufficient period of time to cover the minor disturbances of traffic. The capacities attained for these short periods of time include an entrance delay of 18% of the total time, which delay represents periods when no traffic whatever could reach the bridge roadway due to the interference of intersecting traffic, but it is not considered that the capacity of the bridge was decreased by this percentage as the faster vehicles worked ahead in the open roadway and distributed themselves more or less evenly along the bridge whenever the opportunity offered.

On the Manhattan Bridge, traffic regulations were such that motor vehicles moved in one direction, practically all the time in three lines over the entire 35 foot width of roadway except during short intervals when they traveled in four lines. No horse drawn vehicles were allowed on the bridge. The result of this count is given in the following table:—

MAXIMUM TRAFFIC CONDITIONS, MANHATTAN BRIDGE ROADWAY — AUGUST 31, 1920 — P. M.

Time Interval	Number of Vehicles	Rate per Hour
1 minute	60	3,600
2 minutes	113	3,390
3 minutes	161	3,220
4 minutes	212	3,180
5 minutes	256	3,072
10 minutes	504	3,024
15 minutes	740	2,960
20 minutes	972	2,916
30 minutes	1,389	2,778
60 minutes	2,681	2,681

The above table with all motor-driven vehicles shows a capacity, continuing from five to ten minutes, of about three thousand vehicles per hour. The congested conditions at the entrance

to this bridge, as at the Williamsburg Bridge, caused interruption to the continuous movement of traffic on the day of the count.

On the Brooklyn Bridge, a one-line roadway containing horse-drawn vehicles, reached a capacity for a ten minute period of five hundred sixty-four vehicles per hour, which is slightly greater than was estimated in last year's report for the slowest line of tunnel traffic.

MAXIMUM TRAFFIC CONDITIONS, BROOKLYN BRIDGE ROADWAY — SEPTEMBER 20, 1920

	North Roadway: Motor Trucks and Horses	
Time Interval	Number of Vehicles	Rate per Hour
5 minutes	55	660
10 minutes	94	564
15 minutes	136	534
20 minutes	174	522
30 minutes	237	474
60 minutes	458	458

NOTE: — Trolley cars operate over the second line of this roadway and faster vehicles have an opportunity to pass ahead between cars.

The following table gives the comparison between estimated capacities of a one, two, and three-line roadway as presented in the 1919 Report and the observed capacities resulting from the 1920 traffic counts:—

ESTIMATED AND OBSERVED CAPACITY OF ROADWAY (TRAFFIC IN ONE DIRECTION ONLY)

	Hourly Traffic	Daily Traffic	Annual Traffic
One-line, including horse drawn vehicles:			
Estimated capacity	480	5,850	1,990,000
Traffic count, September 20, 1920	564	.....	.....
Two-line, including horse drawn vehicles in one line:			
Estimated capacity	1,600	19,500	6,635,000
Traffic count, August 30, 1920	1,470	.....	.....
Three-line, all motor driven vehicles:			
Estimated capacity	3,020	36,800	12,500,000
Traffic count, August 31, 1920	3,000	.....	.....

REPORT OF ADVISORY TRANSPORTATION ENGINEERING COMMITTEE

The recommendations in the 1919 Report in regard to the traffic facilities to be provided in the tunnel as to the width of roadway, overhead clearance, probable size of motor vehicles, and operating conditions were made after conferences with manufacturers of motor vehicles, highway engineers, and others. In order to review the recommendations and have the opinion of transportation experts and motor truck manufacturers in the metropolitan district, an Advisory Transportation Engineering Committee was authorized by the Commissions and the Chairman, Mr. H. J. Moran, organized this Committee in June, with the following personnel:

H. J. Moran, Chairman, Engineering Dept., International Motor Corporation; E. A. Williams, President, Garford Motor Truck Company; Frank B. Kurtz, Manager, Truck Dept., Pierce-Arrow Motor Car Company; Charles S. Lyon, Chief Engineer, Packard Motor Car Company; J. H. Cottier, Kelley-Springfield Motor Truck Company; J. F. Winchester, President, Motor Truck

Club of New Jersey; Frank Trumbull, General Motors Company; E. C. Walker, Superintendent of Motor Vehicles, Wm. Farrell & Sons, Inc.; Robert Hebron, R. H. Macy & Company; I. A. Hungerford, Manager, Transport Department, Bordens Farm Products Company; E. E. La Schum, Manager, Motor Vehicle Dept., American Railway Express Company; James Scanlon, Gimbel Bros. Company; James Reardon, U. S. Trucking Corporation; P. V. V. Tobin, Secretary, Howes Transfer & Trucking Company; H. S. G. Brooks, Vice-President, Burns Bros. Coal Company; C. G. Pepoon, Manager, Transport Dept., Tidewater Oil Company; M. J. McDermott, Traffic Manager, James Butler, Inc. Subsequently the Committee was enlarged by the appointment of the following members: W. H. Moore, Manager, Garford Motor Truck Company; F. D. Rutherford, Garford Motor Truck Company; B. K. Rhoads, Assistant Superintendent Motor Transport Department, American Railway Express Company; Frederick C. Horner, Engineer, Packard Motor Car Company.

In September, Mr. Moran resigned as Chairman and was succeeded by Mr. Winchester, who in turn was succeeded by Mr. La Schum, the latter serving until the completion of the work of this Committee. Meetings were held weekly, beginning on July 8th, and, with the exception of the month of August, continued until the early fall when the Committee completed its work and on November 17th submitted final report. All features were considered relative to the tunnel roadway, especial'y (1) width of roadway, (2) ultimate size of the automobile truck, (3) method of operation, (4) roadway surface, (5) method of handling disabled cars, (6) signaling devices and police regulations, and (7) method of cleaning roadway. The report is the result of mature deliberation and a full discussion of traffic conditions to be met in the metropolitan district and in the operation of the tunnel, and endorses in full the plans as adopted and set forth in the 1919 Report. The complete report of this Committee is given in Appendix No. 1.

SURVEYS

A complete system of surveys has been made across the river to establish the alignment of the tunnel. Base lines, approximately 5,000 and 3,400 feet long were laid out and measured in West street, New York City, and Henderson Street, Jersey City, respectively, the ends of which form the triangulation stations. The triangulation was delayed until late in the year on account of the clearer atmospheric conditions in cool weather. Angular measurements were made at night in order to avoid smoke, particularly in the vicinity of the Erie Railroad yards. This triangulation system is connected with the United States Government surveys, and the Hudson and Manhattan Railroad Company's triangulation system. Additional base lines have been laid out supplementing the triangulation system to which all construction and property surveys have been referred.

Topographical and land title surveys of property in the vicinity of the tunnel on both sides of the river are in progress. These surveys include the location of buildings and their subsidiary structures, pavements, walks, parks, railroad tracks, other surface features, and all subsurface structures. Record surveys in the vicinity of the New York land shafts have been made, which include the elevations of pavements, sidewalks, areaways, buildings, and all physical structures on the street surface, so that there may be a complete record in case there is any change in these structures due to tunnel construction.

The datum plane adopted for tunnel construction is 300 ft. below mean high water level in the East river, as determined at the foot of East Twenty-Sixth street, New York City. This is 2.653 feet above mean sea level at Sandy Hook as established by the United States Coast and Geodetic Survey. Elevations have been carried across the river by reciprocal leveling, and checked from data furnished by the Hudson and Manhattan Railroad Company.

Photographs have been taken covering special features which include traffic conditions, methods of work, and general progress. Particular attention has been given to the photographing of streets,. wa ks, parks, buildings, steps, areaways, etc., along the line of the tunnel to establish conditions before the commencement of the work.

DESIGN

The location and type of the New York land shafts was determined after investigation of the cost of tunnel construction to the west (Plate No. 2), open cut construction to the east, shaft construction, acquisition of real estate for the ventilation building, and the operating charges for ventilation as affected by the different locations under consideration. It was decided that the most economical arrangement would be to locate one shaft in Canal Street and the other in Spring Street, immediately west of Washington Street with the building housing the ventilation equipment for both tunnels, located on a 50 foot strip of land to be acquired from the City of New York, immediately west of Washington Street between Canal Street and Spring Street, Plate No. 8. The location of the land shafts in Jersey City was likewise given careful consideration and decided upon after conferences with the Chief Engineer of the Erie Railroad Company so as to minimize interference with the operation of the railroad, Plate No. 13.

On August 12, 1920, contract, plans, and specifications for Contract No. 1 were completed. The contract provides for two structural steel shafts to be sunk as caissons located on the west side of Washington Street, one for the east-bound tunnel in Canal Street, and the other for the west-bound tunnel in Spring Street. The plans also include the necessary re-location of subsurface structures, the most important of which is the large sewer in Canal Street, Plate No. 15. Subsequent to the letting of the contract on October 1st, the contract plans were supplemented by a complete set of working drawings. Shop drawings for the steel work prepared by the Contractor are now being checked and approved.

The contract plans for Contract No. 2, as originally planned, consisted of the two land shafts in Jersey City and about three-hundred feet of approach construction west of the shafts. The plans for the shafts were prepared on two alternative types, one of structural steel and the other of reinforced concrete. The approach sections were of structural steel bent construction embedded in concrete. These plans were completed on September 15, 1920, but have been redrawn as a result of further negotiations with the Erie Railroad, so that Contract No. 2 now consists of two reinforced concrete shafts located about 120 feet west of the bulkhead. The contract plans and specifications were completed in December.

Preliminary studies have been made to determine the most suitable type of pier construction for protection to the tunnel and for the requirements of the Department of Docks of New York City on one side of the river and the Erie Railroad on the other. The design of the Erie Railroad pier provides for two depressed railroad tracks along the center line of the pier which requires the spreading of the tubes to give a clear distance between them of thirty-six feet. This necessitates the construction of an independent shaft for each tunnel. In New York the location of shed columns desired by the Department of Docks makes it economical to locate the tubes with a clearance of about fifteen feet between them which permits the design of the pier shaft for the two tunnels in one unit. Each pier is to be 150 feet wide, extending out to the established pierhead line.

The preliminary design of the cast-iron tunnel, which formed the basis for the estimate of cost submitted in last year's Report, has been investigated in detail for various conditions of loading during and after construction. The loads to which the tunnel will be subjected are indeterminate, and the investigations have been largely in the nature of comparisons between the stresses in the proposed tunnel under assumed conditions of loading with the stresses in tunnels already built under similar conditions. Particular attention has been given to detail comparisons in the proposed lining and those in the lining of other Hudson River tunnels resulting from the active earth pressures corresponding to angles of repose of the surrounding material ranging from 3° to 20° with the maximum depth of cover and water over the tunnel. As a result of these investigations, the design shown on Plate No. 9 has been developed. The investigations are given in detail in Appendix No. 2, which is not complete and is given in preliminary form for information only. This design has the depth of flange and thickness of metal as the preliminary design developed last year and differs only in details. Changes have been made to increase the strength of the joints by increas-

ing the thickness of the metal at the four corners of the segment a maximum of one-half inch and relocating the bolts in the longitudinal joints.

Detail investigations have been made of structural steel for a tunnel lining to be erected behind a shield with a view to its adoption as an alternative design and also of different types of concrete block tunnels. In addition, work has been continued on the design of various types of tunnel sections to be constructed by the trench method with a view to their adoption as alternative plans. Supplementing the trench tunnel sections shown in last year's Report, another type was developed as shown on Plate No. 10.

Studies have been made to determine the detail alignment and grades of the tunnel entrances and exits both in New York and New Jersey and the necessary changes in the grades and widths of streets immediately adjacent in order to provide the best grades and traffic facilities. The tunnel grades are shown on Plate No. 1. Preliminary designs have been made to determine the most economical arrangement of the ventilation ducts in the approach construction, which resulted in locating both ducts above the roadway where the depth of cover permits and on the side of the tunnel structure where the cover is shallow. This construction is shown on Plates Nos. 3 and 4.

The preparation of condemnation maps for the property required for the tunnel approaches and plazas in New York City and Jersey City is in progress. In Jersey City, detail easement maps are being prepared showing all the property and easements required from the Erie Railroad Company. Preliminary plans have been prepared showing the rights and easements required in the yard of the Delaware, Lackawanna & Western Railroad Company. Preliminary plans have also been prepared showing the required changes in the widths of streets in the vicinity of the New Jersey entrance and exit. Maps have been prepared of surveys of surface topography and subsurface structures along the route of the tunnel, this work being nearly completed at the end of the year. Plans and profiles have been prepared showing the detail information obtained from the soundings and borings. A weekly examination has been made in the field and of the public records for filing of plans for construction or alteration of buildings on or adjacent to the lands required for the tunnel approaches with a view to forestalling new improvements on land to be acquired by the Commissions.

Studies of the proper lighting of the tunnel have been continued as it is realized that adequate illumination must be provided. To obtain this result in the limited space available in the tunnel, consideration has been given to the selection and location of types of fixtures best suited for this purpose.

Consideration has been given to the prevention and extinguishing of fires. To confine the areas of the roadway over which gasoline and oil might flow, it is planned to give the roadway a transverse slope toward an open drain under the sidewalk as this would permit liquids to reach the drain at all points and also facilitate cleaning. At the collecting sumps it is planned to make provision for the separation and removal of light oils and gasoline from the water, and the sump chambers will be provided with adequate ventilation to prevent the accumulation of explosive gases. The plans provide for cross-passages between the two tubes at sump locations and elsewhere. These will provide space for the installation of apparatus to cope with any fire which might occur in the tunnel, and it is intended to install, at frequent intervals, small units for emergency use. A water-main will also be laid throughout each tube with hose connections. It is planned to equip the tunnel with an automatic fire-detecting alarm system, which will transmit to a central control station a warning of the occurrence and exact location of fires The system will be adapted to manual operation.

Water may enter the tunnel by leakage through the tunnel lining, from flushing the roadway, rainfall at the approaches, or the breakage of water mains in the tunnel or in the streets. In considering the proper location of the collecting sumps, it is apparent that one should be located at the low point of the tunnel at or near the middle of the river. The construction of the land shafts as pneumatic caissons provides space for a sump of about 25,000 gallons capacity in the space used for a working chamber during construction. In the portion of the tunnel between the land shafts

and the mid-river sump, which will be common to both tunnels, comparatively little water can enter the tunnel. The design of the pier shafts is similar to the land shafts and provides for sumps under the roadway of the same capacity, and it is intended to install pumps of small capacity at these points to serve as an extra precaution in case of shut-down of the pumps at the land shafts. The pumps will be controlled by automatic float switches, so that they will operate only when the water in the sump reaches a fixed elevation. The pipes from the mid-river sump and the river shafts will discharge into the river through the river shafts, while the discharge pipes from the land shafts will be connected to the sewers.

METHOD OF TUNNEL CONSTRUCTION

Three methods for under-river construction were discussed in the 1919 Report; namely, the shield, the trench, and the caisson methods. The shield method was recommended for adoption, the trench method was under consideration, and the caisson method was rejected on account of its difficulties and cost of construction.

The shield tunnel plans have been in progress and the detail drawings have been practically completed. The construction of the tunnel under consideration by the trench method has been given careful study and is not recommended for adoption as an alternative type to the shield tunnel for reasons hereafter given.

In adopting any type of construction it is necessary to give consideration to the physical features not only of the under-river portion of the work but also of the tunnel approaches. In Jersey City, the approach to the waterfront lies under the property of the Erie Railroad Company which insists that the work must be conducted so as not to interfere with the operation of the railroad yard, and in New York City every effort must be made to avoid interference with the use of the streets by the public. The caisson method of construction was considered inside the bulkhead lines but the objection to this method is that in a congested district it interferes with the use of the surface and would result in serious inconvenience to the public and increased damages in the case of the Erie Railroad Company. Construction by excavation from the surface was also considered between the river bulkhead and the land shafts but it was not practicable either in the yards of the Erie Railroad Company or in New York City not only on account of surface interference but also on account of the nature of the material, making this method difficult and dangerous. Accordingly, the shield method was adopted as the most practicable, insuring the least inconvenience and the greatest safety to the public.

With the adoption of the shield method of construction from the land shafts to the river bulkhead, the adoption of the trench method as an alternative type of construction under the river was given most careful consideration. Noteworthy examples of the trench tunnel are those constructed under the Detroit and the Harlem Rivers. (Described in last year's Report.) The plans for the Harlem River tunnel, which was built subsequent to the Detroit tunnel, followed the latter very closely in design and methods of construction. In studying the trench method of construction under the Hudson River, consideration was given to the wide variance in conditions in the Detroit and Harlem Rivers on the one hand and the Hudson River on the other. In this connection, attention is called to the decision of the Public Service Commission as to the method of construction used in building the recent subway tunnels under the East River. The Commission had already adopted the trench method of construction for the Harlem River tunnel, and the same method was considered for the East River crossings, but conditions were so essentially different in the East River from those in the Harlem River that shields were favored for the East River work. In comparing tunneling conditions in the Harlem River, the East River and the Hudson River, it is plainly evident from the width of the river, the great volume of river traffic, waterfront conditions, and conditions of the river bed that, of these rivers, the Hudson River is most suited to shield tunneling. Consequently, if shield tunnels were chosen for the East River in preference to the trench tunnel as built in the Harlem River, so much greater reason would there be for using the shield tunnel in the Hudson River.

The waterfront conditions in the Detroit and Harlem Rivers are favorable to the trench method of construction, in that there are no valuable piers serving large shipping interests; whereas, on both sides of the Hudson River there are valuable piers and waterfront property, interference with the use of which would be an important element of cost which is not nearly so important in the case of shield tunneling, as the work is conducted in such manner as to offer the least interference with waterfront conditions.

Waterway conditions on the Detroit and Harlem Rivers, both as to channel and cross-river traffic, are not comparable with Hudson River conditions, and if a tunnel construction unit of sufficient length for proper prosecution of the work were used in the excavation of a trench across the Hudson River, there would be an unavoidable interference with a great volume of river traffic. A count of river traffic shows that fifteen hundred boats cross the line of the tunnel daily, a record of which is shown on Plate No. 11. Congested river conditions, while serious, to the river traffic, are also of importance in estimating the cost of the trench method because of the hazards to the equipment of construction as well as to shipping itself. The records of the United States Engineer's office for the Port of New York, during the years 1918 and 1919, show that two dredging outfits, working under the direction of that office in the East River where conditions are not as bad as in the Hudson River, suffered sixty-two accidents, five of which caused delays varying from five and one-half to forty-six days. Colonel Edward Burr, United States Engineer Officer in charge of the New York district, in discussing Hudson River conditions before the American Society of Civil Engineers in October of this year, made a statement which bears directly upon water-way conditions which would have to be met during the construction of the tunnel by the trench method. He stated, " Every dredge or other machine working at a fixed position in a channel is an obstruction to traffic, which is greatly increased if moorings are necessary, as in swift tidal currents, and the congestion existing in the main channels of New York harbor, complicated by tidal conditions, creates a most serious problem in the prosecution of operations requiring the use of such machines. Collisions are frequent under these conditions, with resulting increases in the time and cost of prosecuting the work."

From the preceding it would appear that in the opinion of the United States Engineer Officer there is a real hazard involved in carrying on operations from plant anchored in mid-stream. Any collision resulting in the sinking of a tunnel section during the operation of placing it in position would be a very serious matter. The shield method of construction will not interfere with river traffic and therefore no element of cost or damage from that source need be considered. Further, the United States Government has placed very rigorous limitations upon the occupancy of the waters of the Hudson River which require the states to bear the cost of dredging a 1,000 foot channel in the middle of the stream before the trench tunnel could be constructed in the present channel near the New York pierhead line.

The character of the river bed is an important element in the consideration of the practicability of the trench tunnel. The material in the Detroit River is a clay of a consistency that is particularly suited to trench excavation, while in the Harlem River the material is sand and gravel. In the Hudson River the material is a soft silt and rock, the character of the former being such that the volume of excavation that would have to be handled would be unduly large. As to the rock excavation, it would be necessary to blast and remove the debris at a great depth which condition was not found in either the Detroit Tunnel or Harlem River Tunnel. This element of rock, in itself unprecedented, is a serious obstacle. This fact was given the most careful consideration at the time the decision in favor of the shield method was made for the construction of the East River Tunnels through rock and quicksand. Silt conditions in the Hudson River are extremely favorable to the shield method of tunneling, in that if the silt cannot be shoved aside by the shields, it is easily excavated and disposed of through the tunnel. The shield may be closed with the exception of certain openings for the admission of material, which material will be squeezed through these openings into the tunnel as the shield is advanced, requiring no workmen at the face of the heading to shovel the material through the shield. The very condition of the river bed which consti-

tutes a serious difficulty in the case of the trench tunnel, is the one which is most favorable to the shield tunnel; for in the case of the trench tunnel, the soft material greatly increases the volume of excavation, while in the case of the shield tunnel this same material is the most easily excavated of all material.

The trench method of construction would have to be prosecuted under most unfavorable conditions as to interference with river traffic and resulting accidents, which, in every case, will be elements in delaying the work. It is to be expected that storms, fogs and ice would cause a discontinuance of surface work at least two months of each year, so that it is believed that the progress of construction by shields, working under the most favorable conditions, will be greater than by the trench method which has so many difficulties to overcome, as the operations are practically independent of surface conditions and work can be continued throughout the twelve months of the year.

It has been claimed that the trench tunnel would effect a substantial saving in cost over the shield method of construction, based largely upon what has been accomplished in other places or upon proposed innovations in this method of construction. It is to be noted, however, that on account of the uncertainty in regard to dredging the Hudson River silt and the removal of the rock in an open trench, the general attitude of men familiar with dredging conditions has been that this work should be done under some form of cost plus basis or by the rental of dredging equipment rather than upon a straight bid price for yardage in place. The uncertainties of this work, which is of such great magnitude, might involve the Contractor in financial difficulties if he bid anywhere near what would ordinarily be considered a fair unit price.

The estimates which have been made do not support the contention that the trench tunnel is the cheaper of the two methods, and attention is called to the actual bid figures on two recent tunnels representing the two types of construction. In 1912, the Public Service Commission accepted bids for the trench tunnel in the Harlem River amounting to $375.00 per lineal foot of track as compared with bids in 1914 for shield driven tunnels in the East River varying from $388.00 to $425.00 per lineal foot. The latter prices were submitted when the cost of materials was slightly greater than in the former case, and furthermore, the latter tunnels were about one-third in rock, while very little rock was encountered in the Harlem River Tunnel. If this comparison were carried farther to the tunnel under the Hudson River, where, as stated before, conditions for shield tunneling are more advantageous than under the East River, a still lower price for the shield tunnel under the same market conditions can be reasonably expected, due allowance being made for the difference in size of tunnel. The above comparison shows that the claims made by the advocates of the trench tunnel are not consistent with the actual cost of work done heretofore.

Further, the adoption of the shield method of construction for the sections inside the river bulkhead on each side of the river, if the trench method were considered feasible under the river, would require the provision of two sets of tunnel plant, one for the shield tunnel and another for the trench tunnel, and add a very considerable item of expense.

The compressed air and shield method appears to be particularly adapted to the Hudson River, and if it has no advantage over the trench tunnel here, it would appear to have no advantage as a method of subaqueous tunnel construction anywhere.

Counsel has advised that definite plans and specifications must be prepared so that bids will be on a comparative basis and that it is not permissible to ask for bids on general specifications with the privilege of modifying or departing from the Engineer's designs. In a public undertaking carried out by the expenditure of public funds, the first requisite for an alternative proposition must be that it presents an equally assured method of construction, so that those in charge know that they are not involving public expenditure upon doubtful plans but that they are certain of the successful and economical termination of the work. It is believed that any estimate of trench tunnel construction across the Hudson River, on account of the uncertainties, cannot be placed anywhere near upon such a definite basis as the shield driven tunnel. With the preceding in mind, the question appears to be, is it justifiable to recommend a method of construction which depends

for its success upon a number of details which have not been fully worked out under the peculiar conditions found in the Hudson River, when a method is available which has proved under these very conditions to be feasible and practicable and the results of which can be foretold with accuracy and under which accomplishment can be guaranteed?

It is considered that it would be impossible to place the trench tunnel which is so untried, so full of possibilities for delays and unusual situations, on a parity with the recommendation which has already been made for the shield driven tunnel, a type which has been developed along scientific lines through a considerable period of years and which has proved feasible and successful under the very conditions under which this project will be undertaken.

VENTILATION

The ventilation of the Vehicular Tunnel has been carefully studied, as it was recognized that the question of adequate ventilation was one of the most important problems in the planning of the tunnel. The tunnel is about 8,300 feet long between portals and is to carry two lines of traffic in each direction, estimated at 1,900 vehicles per hour. The present ferry traffic is divided about equally between horsedrawn and motor vehicles, but the requirements for the ventilation of the tunnel should be based upon all motor vehicles. This is a problem in ventilation unlike any heretofore solved, both in character and magnitude.

There are vehicular tunnels in different parts of the world, but none is comparable with the Hudson River Tunnel either in length or in character and volume of traffic. Years ago three vehicular tunnels were constructed in Chicago under branches of the Chicago River, but they are comparatively short and were later given over to the exclusive use of street cars. In 1893 a vehicular tunnel, 700 feet long between elevator shafts, was opened in Glasgow, Scotland. About 1912 a similar tunnel was opened in Hamburg, Germany, under the River Elbe. This tunnel is 1,471 feet long between elevator shafts and consists of two separate tubes, each tube providing a roadway of sufficient width to accommodate one line of vehicles and two sidewalks.

The only existing vehicular tunnels even approximately comparable to the Hudson River Tunnel are the Blackwall and Rotherhithe Tunnels under the Thames River in London. The Blackwall Tunnel, which was opened for traffic in 1897, has an under-river length of 1,221 feet between shafts and a total length between portals of 6,200 feet, with four ventilating shafts in all. It consists of a single tube twenty-seven feet in diameter with a roadway of sufficient width to accommodate one line of traffic in each direction and two sidewalks. Traffic counts in 1920 show that the maximum number of motor vehicles using the tunnel is less than one hundred per hour. The Rotherhithe Tunnel is thirty feet in diameter and similar to the Blackwall Tunnel in traffic facilities, the length of the under-river section between shafts being 1,570 feet. The records show that traffic is somewhat less than in the Blackwall Tunnel. All of these tunnels are ventilated by the natural movement of the air through the shafts and the portals. Plans for the installation of mechanical ventilation in the Rotherhithe and Blackwall Tunnels have been under consideration for the past few years. It is reported that at times the atmospheric conditions in these tunnels are bad, but there is no record of any one having been overcome. From the experience in the London Tunnels and realizing the composition of the automobile gases and considering the greater length of the Hudson River Tunnel between shafts and the large volume of motor traffic to be handled, it is not possible to rely upon natural ventilation and it is necessary to use forced ventilation. Sufficient ventilation must be provided to make the tunnel safe and comfortable, and it is of importance that this be accomplished at a minimum cost of construction and operation. To this end the ventilation of the tunnel has been investigated under three subdivisions:

I. THE AMOUNT AND COMPOSITION OF EXHAUST GASES FROM MOTOR VEHICLES.

II. THE DILUTION NECESSARY TO RENDER THE EXHAUST GASES HARMLESS.

III. THE METHOD AND EQUIPMENT NECESSARY FOR ADEQUATE VENTILATION.

I

THE AMOUNT AND COMPOSITION OF EXHAUST GASES FROM MOTOR VEHICLES

The impurities in the atmosphere of a tunnel used by motor vehicles are the products of combustion of gasoline. If complete combustion occurred, the carbon content in the gasoline would be found in the exhaust gases in the form of carbon dioxide. This gas is objectionable but can be tolerated in considerable quantities without injurious effects. In a gasoline engine, however, complete combustion seldom, if ever, takes place with the result that in addition to the carbon dioxide the exhaust gases contain varying percentages of unsaturated hydrocarbon (smoke) and carbon monoxide, dependent upon the completeness of combustion.

As carbon monoxide is poisonous, the quantity of this gas in the exhaust gases determines the ventilation requirements. In other words, if sufficient fresh air is supplied to reduce this gas to a safe percentage, the other gases and impurities present, such as carbon dioxide, methane and smoke, will also be diluted sufficiently. The important consideration in this phase of the work, therefore, was to determine the amount of carbon monoxide which would be liberated in the tunnel. For this purpose an extensive search was made of literature on this subject, but it was found that there were no data from which a satisfactory determination could be made.

As already stated, the amount of carbon monoxide in the exhaust gases is dependent upon the degree of combustion of the gasoline fuel, which is dependent upon a number of variable factors, so that it is impossible to determine theoretically the percentage of carbon monoxide in the exhaust. The only way the amount of this gas could be determined was by actual tests on gas engines under operating conditions, and very little experimental work along this line had been done.

Tests which had been performed on automobiles and gasoline mine locomotives had been mainly for the purpose of determining the combustion efficiency of such engines, and while they afforded a guide on which to base the preliminary ventilation calculations, they were not sufficient to serve as a basis for the final ventilation design. To establish such a basis it was necessary to perform independently further tests to determine the amount and composition of the exhaust gases from motor vehicles under actual operating conditions.

II

THE DILUTION NECESSARY TO RENDER THE EXHAUST GASES HARMLESS

A sufficient volume of fresh air must be supplied to make the atmosphere harmless and comfortable for those using the tunnel. Normal air contains no carbon monoxide but does contain small quantities of carbon dioxide amounting in some cities to as much as five parts in 10,000. Carbon monoxide is an active poison as it has an affinity for the hemoglobin of the blood much greater than that of oxygen, so that the blood absorbs carbon monoxide more readily than it does oxygen and to the extent to which the blood is saturated with carbon monoxide, its ability to transport oxygen to the organs and tissues of the body is reduced. The symptoms of carbon monoxide poisoning are headache, nausea, weakness of the limbs, and, in the severer cases, unconsciousness. An exhaustive search was made of available information on this subject and while there are numerous publications dealing with it, there was no general agreement as to the amount of carbon monoxide which could be breathed a given length of time without injury or discomfort.

The most extensive research work in determining the effects of carbon monoxide on the human system had been performed by the English authority, Dr. John S. Haldane. He carried out experiments on himself and others in the Metropolitan Railway Tunnel in London while this Tunnel was being operated with steam locomotives. He also performed a number of laboratory experiments on himself by breathing air containing varying percentages of carbon monoxide for varying periods of time.

Dr. Haldane states that on the whole there is every reason to attribute the symptoms produced by carbon monoxide solely to the diminution of the oxygen carrying power of the blood. The symp-

toms produced in a healthy and normal person resemble very closely those produced by atmospheres in which the oxygen tension is considerably diminished either by reduction of atmospheric pressure or reduction of the oxygen percentage. When the person again enters normal air all carbon monoxide will have disappeared from the blood after a few hours. Dr. Haldane is of the opinion that there is no reason to suppose that regular exposure to the atmosphere of the tunnel, referring to the Metropolitan Tunnel in London, produces ill effects or shortens the life of any healthy person; this is borne out by the sickness and mortality statistics of the railroad company. The men employed on the line were exceptionally healthy in spite of the constant exposure to the impure air of the tunnel.

The work performed by Dr. Haldane was very extensive, but due to the fact that the duration of the exposure to carbon monoxide is an important factor in the quantity absorbed by the blood, and therefore in the physiological effect, his findings could not be directly applied to conditions in the Vehicular Tunnel, where the time of exposure would be of much shorter duration than was the case with passengers and operating crews of the Metropolitan Tunnel. From his experience, it appeared that a concentration of from three to five parts carbon monoxide to 10,000 parts of air would be safe figures to use. While it is of the greatest importance to have the Vehicular Tunnel adequately ventilated, it is also of importance to know the exact amount of air required for this purpose, as that has an important bearing on the size of the tunnel and the cost of operation. For example, with the method of ventilation proposed, the power required for handling the air for a dilution to five parts in 10,000 would be only 22 per cent of that required for a dilution to three parts in 10,000.

To obtain an adequate and economical design for the ventilation layout of the tunnel, it was therefore considered necessary to perform extensive experiments and in November, 1919, a contract was made with the United States Bureau of Mines, in which the Bureau of Mines agreed to conduct these experiments with their staff of experts and such assistants as it might become necessary to engage for this purpose. The investigations were to be carried out under the direction and in accordance with a program outlined by your Engineer.

EXPERIMENTAL INVESTIGATIONS TO DETERMINE THE AMOUNT AND COMPOSITION OF EXHAUST GASES FROM MOTOR VEHICLES

The investigations to determine the amount and composition of exhaust gases from motor vehicles were carried out at the Bureau of Mines Experiment Station at Pittsburgh, under the direct supervision of Mr. A. C. Fieldner, Supervising Chemist of the station. The work was to be completed by March 1, 1920, but due to the unusually severe weather conditions last winter the road tests were considerably delayed so that the contract was extended to September 30, 1920, and the final report was submitted on November 1, 1920.

The schedule called for the testing of passenger cars and trucks of various makes and capacities. The tests were made with car loaded and light, car standing with engine racing and idling, accelerating from rest on level grade and on maximum grade, running at three, six, ten, and fifteen miles per hour on level, and up and down a grade of 3½ per cent, corresponding to the maximum tunnel grade. The tests were performed on streets with pavements corresponding to the roadway of the tunnel. The gas samples were taken directly from the exhaust pipe throughout the entire duration of the test. A total of one hundred one cars was tested to determine the quantities of carbon monoxide produced per minute by the various types of cars under the conditions specified.

The motor vehicles tested were classified in four groups — passenger cars, trucks under two-ton capacity, two to five-tons, and five tons and over. The average results of all road tests show that at a speed of six miles per hour the exhaust gases of trucks contained the following percentages of carbon monoxide: 7.44 on up-grade, 5.38 on down-grade, and 7.56 on level-grade, with corresponding quantities of carbon monoxide in cubic feet per car per minute, 1.95, 0.72, and 1.40. At a

speed of ten miles per hour, the corresponding percentages for trucks were 6.20, 6.22, and 7.30, and for passenger cars, 7.03, 6.30, and 7.19, with corresponding quantities of carbon monoxide in cubic feet per car per minute for trucks, 2. 43, 1.21, and 1.99, and for passenger cars, 1.33, 0.62, and 0.99. The average percentage of carbon monoxide content in the exhaust gases for all cars tested were, with engines idling, 6.72; engines racing, 7.37; accelerating from rest up maximum grade, 6.40; with corresponding quantities of carbon monoxide in cubic feet per car per minute, 0.644, 1.53, and 2.11. The fact that the quantity of carbon monoxide produced per minute with engine idling is small shows that where traffic is blocked and the cars are crowded closer together than during normal operation, the ventilation requirements would be no greater than during normal operation.

The experiments also included the determination of the heat produced by the combustion of gasoline and it was found that one pound of gasoline produced 14,910 British Thermal Units. In general, the results of the test show that the exhaust gases contained about 6.8 per cent carbon monoxide and 8.4 per cent carbon dioxide, developing only 67 per cent of the heat value of the gasoline, so that about one-third of the gasoline fuel used for motor vehicles is wasted through incomplete combustion. The complete report of these investigations is given in Appendix No. 3.

EXPERIMENTAL INVESTIGATIONS TO DETERMINE THE PROPER DILUTION TO RENDER THE EXHAUST GASES HARMLESS

The experiments to determine the proper dilution to render the exhaust gases harmless were conducted at the Bureau of Mines Experiment Station at Yale University under the direction of Dr. Yandell Henderson, Consulting Physiologist. The experimental investigations on this problem were completed during March, 1920, and the final report was submitted by the Bureau of Mines on November 1, 1920.

The principal questions to be answered by the experiments were as follows:

The maximum amount of carbon monoxide that may be absorbed without producing discomfort.

The rates at which a person driving a car will absorb carbon monoxide from atmospheres containing various amounts of this gas.

The influence of any physical exertion upon the volume of breathing and so upon the rate of absorption of carbon monoxide.

The determination as to whether there are other toxic substances than carbon monoxide present in automobile exhaust gases.

The investigation of the possibility of individual variations in the susceptibility to carbon monoxide poisoning.

The experiments were performed in a gas-tight chamber of two hundred twenty-six cubic feet capacity. Members of the staff spent periods of one hour in amounts of carbon monoxide varying from two to ten parts in 10,000. In addition to these experiments, tests were also performed on a large number of persons in a chamber of 12,000 cubic feet capacity with an automobile engine running and exhausting into the chamber. The duration of all tests was one hour. The length of time required to travel through the tunnel from portal to portal at a speed of three miles per hour is 31.4 minutes, and therefore the duration of one hour for the tests was considered to be sufficient. The average speed of passenger cars through the tunnel will probably be not less than ten miles per hour, requiring at this speed only 9.4 minutes for passage. It is considered that a standard adopted on the basis of forty-five minutes time in the tunnel will assure the safety of passengers.

The conclusions in the report may be briefly summarized as follows:

When an automobile engine with gasoline as a fuel is running properly the exhaust contains no substance which is toxic to any appreciable extent other than carbon monoxide. Gasoline engines with cylinders missing or when cold, over-supplied with oil or gasoline, or smoking from any cause, may throw off disagreeable vapors irritating to the eyes and nauseating to some persons.

The physiological effects of carbon monoxide are wholly due to the union of this gas with the hemoglobin. To whatever extent that the hemoglobin is so combined, by that amount it is rendered incapable to transport oxygen to the organs and tissues of the body. The combination of carbon monoxide and hemoglobin is a reversible reaction, so that when a person returns to fresh air the carbon monoxide is gradually eliminated. Of all physical signs and tests of carbon monoxide poisoning, headache proved the most definite and reliable. Concentrations of gas too weak or periods of exposure too short to induce this sign are to be considered harmless. No one had this sympton to an appreciable degree after a period of one hour in the chamber with four parts of carbon monoxide. With six parts the degree of effect, if any, was usually very slight, while with eight parts there was decided discomfort for some hours, although not enough to interfere with the continuance of efficient work in the laboratory or at the desk.

The following table summarizes the experimental results for one hour's exposure to various concentrations in the chamber:

Parts CO in 10,000 parts of air breathed	Corresponding equilibrium value for the blood percentage saturation	Percentage saturation in the blood after one hour	Headache
2	23	11–12	None
4	36	16–20	None
6	47	18–26	None or slight
8	53	32–34	Distinct
10	58	38	Marked for several hours

The second column of this table gives the blood saturation that would result if the person stayed in the concentration indefinitely; the third column the saturation in one hour. The table shows that for concentrations not exceeding six parts in 10,000 the blood saturation after one hour's exposure would be about one-half the saturation that would result with the same concentrations for an indefinite exposure. In any atmosphere containing a uniform amount of carbon monoxide, almost all the gas inhaled at first is absorbed, but the successive increments of gas absorbed thereafter grow less and less as time goes on. If a man exercises sufficiently to double his volume of breathing he absorbs as much carbon monoxide in one-half hour as he does at rest in one hour. In no person examined was there found to be any unusual individual susceptibility.

Passengers in cars going through the tunnel in about ten or fifteen minutes will absorb very little gas. This affords a safe margin for the ample protection of children and invalids. In conclusion the report states as follows:

"Finally it should be emphasized that the standard here proposed for exposure of forty-five minutes — four parts in 10,000 or its equivalent in various concentrations up to six in 10,000 — is designed to afford not only complete safety, but also comfort and freedom from disagreeable effects. Risk of considerable discomfort would begin at from eight to nine parts of carbon monoxide in 10,000 of air for periods of an hour at rest, or for shorter periods during exertion. Actual danger would begin with concentrations not very much higher, and periods not very much longer."

In this connection it is of interest to note the opinion of Dr. Haldane on these experiments as stated in a letter to Dr. Henderson:

"What I should say now is that with long exposures of several hours, anything more than .02 per cent. should be avoided. For exposures of less than an hour .05 per cent. would not be really objectionable. As regards gases from motors, however, the smoke and smell might possibly be worse than the CO. On this point I have no experience though I have run across cases of poisoning where there does not seem to have been much smoke or smell.

"You will see from the above that my ideas about CO coincide very closely with what your experiments point to."

This shows that two foremost authorities on carbon monoxide poisoning are in full agreement that the standard recommended for the tunnel — a uniform concentration of four parts carbon

monoxide in 10,000 of air, or its equivalent, in various concentrations — is not only a safe but a conservative figure. The complete report of these investigations is given in Appendix No. 4.

III

THE METHOD AND EQUIPMENT NECESSARY FOR ADEQUATE VENTILATION

After having established reliable figures for tne amount and composition of exhaust gases from motor vehicles of various types and sizes and the proper dilution to render the exhaust gases harmless, it is then necessary to determine the number of vehicles of each type which will use the tunnel at capacity operation so that the amount of fresh air required in the tunnel can be determined.

The estimated capacity of the twenty foot tunnel roadway with two lines of motor vehicles operating in the same direction is 1,900 vehicles per hour. In calculating the ventilation requirements, however, this number has been increased as a basis for determining the amount of fresh air required. Assumed speeds and spacing in the two lines of traffic have been used, giving a total of 2,113 vehicles per hour, or about 11 per cent. greater than the estimated capacity of the tunnel. It has further been assumed that all vehicles will be operated with gasoline motors, but a number of the vehicles will be horse drawn or electrically operated, so that the excess is greater than 11 per cent.

The following table gives the classification of vehicles, the speed, and spacing used in these calculations:

ESTIMATE OF TRAFFIC FOR VENTILATION REQUIREMENTS

	Speed M. P. H.	Spacing, Feet	Vehicles per Hour	Per cent of Total Traffic	Vehicles in Tunnel
Fast Line	10	40	.....	.....	.....
Pleasure cars	.....	.....	360	17	57
Trucks less than 2-ton capacity	.....	.....	180	8.5	28
Trucks: 2 to 5 tons	.....	.....	780	37	123
Slow Line	6	40	.....	.....	.....
Motor trucks 5 tons and over	.....	.....	793	37.5	208
	.....	.....	2,113	100.0	416

The present traffic on the ferries nearest the tunnel consists of about 43 per cent horse drawn vehicles, 38 per cent motor trucks of all capacities, and 19 per cent pleasure cars. It is expected that the construction of the Vehicular Tunnel will revolutionize the vehicular traffic across the Hudson River and, in the absence of any reliable data on which to base the future classification of this traffic, that shown in the above table is adopted, as it is desirable to be on the side of safety by overestimating rather than underestimating.

The road tests on motor vehicles show that the volume of carbon monoxide produced varies with the gradients. For the conditions of traffic as given in the table, 293 cubic feet of fresh air per minute per foot of up-grade are required, 124.6 cubic feet for the down-grade, and 224.5 cubic feet for the level-grade. The following calculations are based on the above figures, each tube being considered separately. The sections from the tunnel portals to the street surface will be either entirely open or sufficiently open to allow of natural ventilation.

The following tabulation shows the amount of fresh air in cubic feet per minute required on the various grades:

	Up-grade	Level-grade	Down-grade	Total
North tube	810,145	757,687	266,074	1,833,906
South tube	701,735	757,687	323,277	1,782,699

This represents fifty-four, forty-two and twenty-three air changes per hour on the up-grades, level-grades and down-grades, respectively, or an average of forty-one changes per hour for the north tube and forty changes per hour for the south tube. In considering the method of ventilation two general methods have been studied; namely, longitudinal and distributive.

LONGITUDINAL METHOD OF VENTILATION

In the longitudinal method of ventilation the entire cross-section of the tunnel above the roadway would be utilized as a duct for conveying the air through the tunnel. The air would be supplied through blower fans near one portal and enter the tunnel through a nozzle or nozzles at a velocity which, converted into pressure, would be sufficient to force it through the entire length of the tunnel. The percentage of CO would vary from zero at the entrance to a maximum at the exit. If this maximum is 6 parts in 10,000, the result is the same as though the tunnel had a uniform percentage of 4 parts in 10,000 throughout its entire length. This method of ventilation is used extensively in railroad tunnels where the traveling public is protected in closed cars from the disagreeable effects of high air velocities.

In a vehicular tunnel excessive air velocities would be objectionable. If in a twenty-nine foot tunnel the air is introduced into the north tube near one portal through a nozzle having a cross-sectional area of seventy-four square feet and is exhausted through the opposite portal, the air would have a nozzle velocity of about 282 miles per hour. This would produce a velocity of seventy-two miles per hour in the tunnel at points where the roadway is occupied by one pleasure car and one large body truck abreast, or a velocity of fifty-one miles per hour where there are no vehicles. These air velocities are too high to be permitted in a vehicular tunnel, and in addition, the power required for handling the air by this method would be high. Modifications of this method have been studied, introducing two and four shafts between the portals to avoid the necessity of forcing the air through the entire length of the tunnel. This would reduce the air velocities in the tunnel as well as the power requirements, but even with the four shafts the maximum air velocities are considered to be too high for comfort. In addition, it would be very difficult to exert a definite control over the flow of the air. Vitiated air to be withdrawn through a certain opening might readily move by this opening, resulting in non-uniform and possibly insufficient ventilation. The longitudinal method of ventilation and its various modifications involve many uncertainties depending on the nature and volume of traffic, the effects of outside winds, and other influences. Several combinations of the longitudinal and distributive methods of ventilation have been studied. Some of these indicate a reduction in power requirements, but most of them have one or both of two serious defects; namely, high air velocity or lack of definite control.

DISTRIBUTIVE METHOD OF VENTILATION

In the distributive method of ventilation the air is introduced into and exhausted from the tunnel through a number of openings at frequent intervals leading from the tunnel roadway. This method avoids excessive air velocities in the tunnel as there will be no longitudinal flow of air through the roadway except that caused by outside winds and the moving of traffic. These will be opposed and may entirely neutralize each other in one tube, while in the other they will tend to produce air currents in the same direction. These air currents will not be sufficiently strong to be objectionable from a traffic point of view, nor are they sufficient to relieve appreciably the mechanical equipment.

The distributive method of ventilation is believed to be better suited for the Vehicular Tunnel than the other methods which have been considered, for the following reasons:

1. Fresh air is supplied at all points throughout the tunnel.
2. The air supplied at any point can be controlled.

3. There will be no discomfort or danger from high velocity air currents.

4. The ventilation of the tunnel will not be affected by moving traffic or the direction of the wind.

5. Exhaust gases will be quickly diluted and removed.

A circular tunnel provides spaces above and below the roadway for air ducts. The best location of these air ducts has been given consideration and it appears that the fresh air duct should be located under and the exhaust duct over the roadway. The fresh air, supplied by blower fans at the shafts, will be discharged from the main duct through adjustable openings into continuous expansion chambers on each side of the roadway, from which the air will escape into the tunnel. The exhaust duct, located above the roadway and connected with the exhaust fans at the shafts, will have openings of varying sizes provided with adjustable shutters. By making the openings for the intakes and outlets adjustable it will be possible to regulate the volume of air supplied and withdrawn so as to meet the requirements of traffic.

The power required for moving the air through the ducts increases very rapidly with their length, so that it is important to make them as short as possible. To save operating costs each tunnel will have four ventilating shafts, two located near the pierhead line and the others about midway between these and the portal. The equipment in the shaft superstructures will furnish ventilation half way to each of the adjacent shafts. The width of the river between established pierhead lines is about 3,210 feet, within which space nc obstruction can be placed, so that each river shaft is located as near the pierhead line as is consistent with the safe protection of the shaft, within protective piers built over the tunnel. The distance between river shafts is 3,375 feet.

VENTILATION EQUIPMENT

Fans to handle the required amount of air are to be installed, with a sufficient number of spare units to insure a full air supply at all times. The fresh air is to be supplied to the fans through open louvres in the sides of the buildings and the vitiated air exhausted through vertical stacks. The fans are to be electrically driven, current for which may be generated in an independent plant or obtained from the power companies serving New York City and Jersey City. If the ventilation equipment is inter-connected with independent generating stations, the possibility of an interruption in the power supply will be eliminated. If, in addition, it should be considered desirable to install storage batteries for the emergency operation of the fans, sufficient space is available within the buildings for such installation.

Natural movement of air through the tunnel may result from surface winds, moving traffic, or from heat generated in the tunnel. It is impossible to make an exact estimate of the effect of these causes, as they are considered to be of such uncertain nature as to be of value only under favorable conditions. Surface wind may be entirely absent on days when ventilation is most needed and at other times their effect may be neutralized by traffic moving in the opposite direction. The effect of the difference in temperature between the tunnel atmosphere and the outside air is also uncertain, as it is not expected that the temperature in the tunnel will be very much above that of the outside air. While it is questionable whether a combination of natural and mechanical ventilation will function properly, it is certain that the mechanical ventilation must have sufficient capacity to ventilate the tunnel properly without aid from natural ventilation. It is possible that natural ventilation would be sufficient if the number of motor vehicles should not exceed fifty per hour. The saving in shutting down the mechanical equipment and depending on the natural ventilation would be very slight, as with the small volume of fresh air required at that time the power charge would be nominal only. Although it is not expected to rely upon natural ventilation in planning the shafts, provision has been made for the installation of flues so that advantage can be taken of natural ventilation.

The sources of heat in the tunnel are the combustion of gasoline, the lighting system, friction in the air ducts, and the persons traveling through the tunnel. Taking into consideration the

heat developed from these sources, the loss of heat by radiation through the tunnel walls, and the total number of forty air changes per hour required at maximum operation, the rise in temperature will not be sufficient to cause discomfort to those passing through the tunnel. Investigations are being made to determine the heat dissipation through the tunnel walls and other questions relating to the temperature of the tunnel.

ADDITIONAL EXPERIMENTS

Following the completion of the experimental investigations to determine the amount and composition of exhaust gases from motor vehicles and the dilution necessary to render these gases harmless, sufficient information was at hand to determine the amount of fresh air required to provide adequate ventilation for the tunnel. All the investigations which have been carried on during the year substantiate the advisability of adopting the method which was outlined in the 1919 Report. The main questions remaining to be decided are the practical working out of the various details of this scheme and the power required to move the air through the ducts, and it is considered necessary to perform further experiments so that, in the design of the tunnel, the additional cost of construction due to an increase in the size of the air ducts may be compared with the resulting saving in operating charges.

Careful consideration has been given to the proper method and agency for conducting these experiments and this has resulted in an agreement with the United States Bureau of Mines for carrying out the following additional experiments:

1. Determination of the coefficient of friction of flow of air in concrete ducts.
2. Verification of formulae used in computation of power required for moving air through a duct from which air is taken off at intervals.
3. Determination of power losses in bends.
4. The diffusion of exhaust gases in the cross section of the tunnel.
5. Temperature conditions in the proposed tunnel as affected by the operation of internal combustion motors.
6. Physiological effects of temperature, exhaust gases, and smoke in the tunnel section under operating conditions.

The group of experiments listed under one, two, and three, with such other detailed experiments as may be decided upon are to be performed at the engineering experiment station of the University of Illinois, and the group of experiments listed under four, five, and six, with such additional details as may be decided upon, are to be performed at the experimental mine of the Bureau of Mines at Pittsburgh. The experiments are to be carried out under the direction of your Engineer.

As the Bureau of Mines is desirous of having the information to be obtained from these experiments for use in connection with mining, the expense of these experiments will be shared by the two states and by the Bureau of Mines. A report on the series of experiments to be performed at the University of Illinois is to be submitted following which it is expected that all information necessary to form the basis for an adequate and economical design of the ventilation ducts for the tunnel will be at hand.

SCHEDULE OF CONTRACTS

The adopted schedule of contract, plans, and specifications with the probable time of completion of each contract is submitted herewith with a brief description of the work comprising each contract. This schedule is tentative, subject to change depending upon the exigencies of the work:

Contract	Contract, Plans and Specifications To be Ready	Contract to be Delivered	Contract to be Completed
No. 1. New York Land Shafts	Aug. 16, 1920	Oct. 1, 1920	Oct. 1, 1921
No. 2. New Jersey Land Shafts	Jan. 1, 1921	Mar. 15, 1921	Jan. 15, 1922
No. 3. New York River Tunnel and Shafts	May 15, 1921	July 1, 1921	July 1, 1924
No. 4. New Jersey River and Land Tunnels and River Shafts	May 15, 1921	July 1, 1921	July 1, 1924
No. 5. New York Approach	Nov. 15, 1921	Jan. 1, 1922	July 1, 1924
No. 6. New Jersey Approach	May 15, 1922	July 1, 1922	July 1, 1924
No. 7. Ventilation Equipment Buildings, New York	Nov. 15, 1922	Jan. 1, 1923	July 1, 1924
No. 8. Ventilation Equipment Buildings, New Jersey	Nov. 15, 1922	Jan. 1, 1923	July 1, 1924
No. 9. Installation of Tunnel and Ventilating Equipment	May 15, 1923	July 1, 1923	Dec. 31, 1924

Refer to Plate No. 12 for location of contracts.

Contract No. 1 provides for the construction of two land shafts in Manhattan, the relocation of the New York Central tracks in Canal Street, the relocation and reconstruction of surface and subsurface structures in Spring and Canal Streets which are interfered with by the shaft structures, and the building of an engineer's field office.

This Contract was advertised on August 24, 1920, and bids were received from five contractors on September 20, 1920. A detailed summary of the bids received, together with the engineer's estimate, is given in Appendix No. 5. The lowest bid, amounting to $650,802.50, was that of Thomas B. Bryson, Vice-President of the Holbrook, Cabot and Rollins Corporation, and the contract was awarded to this corporation on October 1, 1920. The Contract Time is one year. On October 12th, construction was started with the breaking of ground at the Canal Street shaft, in the presence of officials of both states and about two thousand invited guests. The relocation of the New York Central tracks and all subsurface structures in Canal Street to avoid interference with the shaft structure was completed in December, Plates Nos. 14 and 15. The reconstruction of the large Canal Street Sewer, which was started in October, is about one-half completed. The sub-contract for the fabrication of the steel for the caissons was awarded by the contractor to the American Bridge Company. Fifty per cent of the shop drawings have been completed and checked. Thirty-five per cent of the steel required has been rolled and is in the fabricating shops. Payments on Contract No. 1, amounting to $39,348.41, were made during the year.

Contract No. 2 provides for the construction of the New Jersey land shafts located in the Erie Railroad yards. Plans for this contract are ready, but work cannot be started until an agreement with the Erie Railroad Company has been consummated.

Contract No. 3 provides for the construction of the New York river shaft located near the pierhead line, and the land and river tunnels from the Spring and Canal Street shafts extending westward under Spring, Canal, and West Streets and the Hudson River to a junction with Contract No. 4, approximately 1,500 feet west of the New York bulkhead line. Plates Nos. 2, 6, and 7.

Contract No. 4 provides for the construction of the New Jersey river shafts near the pierhead line, and the land and river tunnels from a point in the Erie Railroad yards approximately 800 feet west of the bulkhead, and extending eastward under the Erie Railroad yards, and waterfront and the Hudson River to a junction with Contract No. 3, approximately 1,500 feet west of the New York bulkhead line.

Contract No. 5 provides for the construction of the New York approaches in Spring and Canal Streets, the northerly tunnel under Spring Street extending eastward from the Spring Street shaft to the easterly side of Hudson Street, and under private property and Dominick Street to the street surface at Broome Street midway between Hudson and Varick Streets; the southerly tunnel under Canal Street extending eastward from the Canal Street shaft to the easterly line of Hudson

Street and under Canal Street and private property to the street surface at Canal, Vestry, and Varick Streets.

Contract No. 6 provides for the construction of the New Jersey approaches, the northerly tunnel from the westerly end of Contract No. 4 and extending westward under the Delaware. Lackawanna & Western Railroad yards and private property to the street surface at Fourteenth Street and Provost Street; the southerly tunnel from the westerly end of Contract No. 4 and extending westward under the Erie Railroad Company's property to the street surface at Provost and Twelfth Streets, Plate No. 13.

Contract No. 7 provides for the construction of the ventilation equipment buildings at the land and river shafts in New York.

Contract No. 8 provides for the construction of the ventilation equipment buildings at the land and river shafts in New Jersey.

Contract No. 9 provides for the furnishing and installation of the equipment necessary for the operation of the tunnel.

INSPECTION OF MATERIALS

The specifications provide for construction materials best suited for the work, and to this end it is necessary not only to inspect the incorporation of the materials into the work but also to inspect the materials at the source in order to make certain that they conform to the required standards. The inspection of the material after it is delivered on the work is taken care of by the engineers in charge of construction, but all inspection up to that time must be done by specially trained men at the point where the materials are manufactured.

The generally accepted method on large work is to organize an Inspection Bureau such as has been done in connection with the construction of the New York subways and the New York State Barge Canal. In view of the very considerable expenditure which the creation of the above mentioned facilities would involve at this time and of the fact that there are already such facilities available, it is expected that arrangements will be made whereby the present inspection may be done through the inspection departments of the Transit Construction Commissioner, and the State Engineer. It is considered that this arrangement will promote economy during the early stages of the tunnel work as the inspection force depends largely on the variety of materials and the different localities in which they are produced.

ORGANIZATION

In the conduct of highly specialized technical work it is of the utmost importance to have a competent engineering staff not only in technical training but also in thorough experience in the special problems of construction. There is probably no field of engineering in which success is more dependent upon special experience than that of subaqueous tunnel construction. In the selection of staff assistants, appointments were made so as to obtain only those specially qualified to supervise the work through years of experience. Those in charge of the work are technically trained men who have had not less than ten years' experience in subaqueous tunneling gained since 1903 in the construction of under-river crossings in New York and elsewhere. Subordinate engineering positions have been filled so that responsibility will be placed upon assistants who have had experience in this highly technical work.

The appointments to the staff have been made with great care as to physical fitness so that when tunnel construction is actively in progress the force will not be depleted due to its inability to work under compressed air. Physical fitness is a prime requisite for compressed air work and the Commissions are required by law to employ in this work only those who have passed a rigid physical examination. Accordingly, all candidates for appointment have been required to pass such an examination.

The general organization has continued the same as last year. The engineers reporting directly to the chief engineer are:

Mr. Jesse B. Snow, Principal Assistant Engineer.
Mr. Milton H. Freeman, Division Engineer.
Mr. Ole Singstad, Designing Engineer.

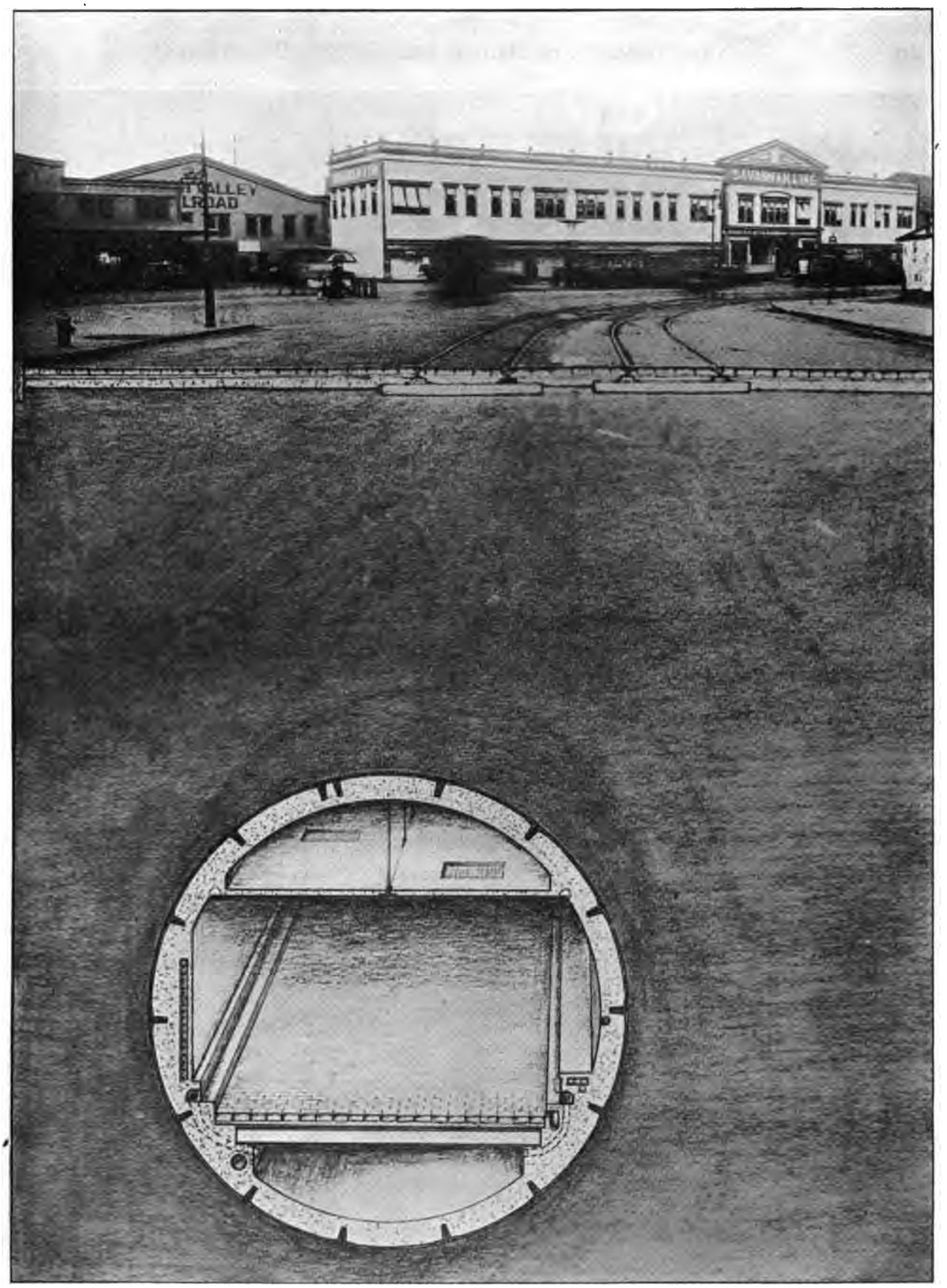
Major John A. Bensel, Mr. William H. Burr, Mr. Edward A. Byrne, Mr. J. Vipond Davies, Colonel George L. Watson, and Mr. William J. Wilgus have served as members of the Board of Consulting Engineers. The late Professor John R. Allen served as Consultant on Ventilation up to the time of his death and has been succeeded by Professor Arthur C. Willard. Mr. Lewis F. Pilcher has acted as Consulting Architect, and Dr. Edward Levy as Consulting Physician.

Respectfully submitted,

(Signed) C. M. HOLLAND,
Chief Engineer.

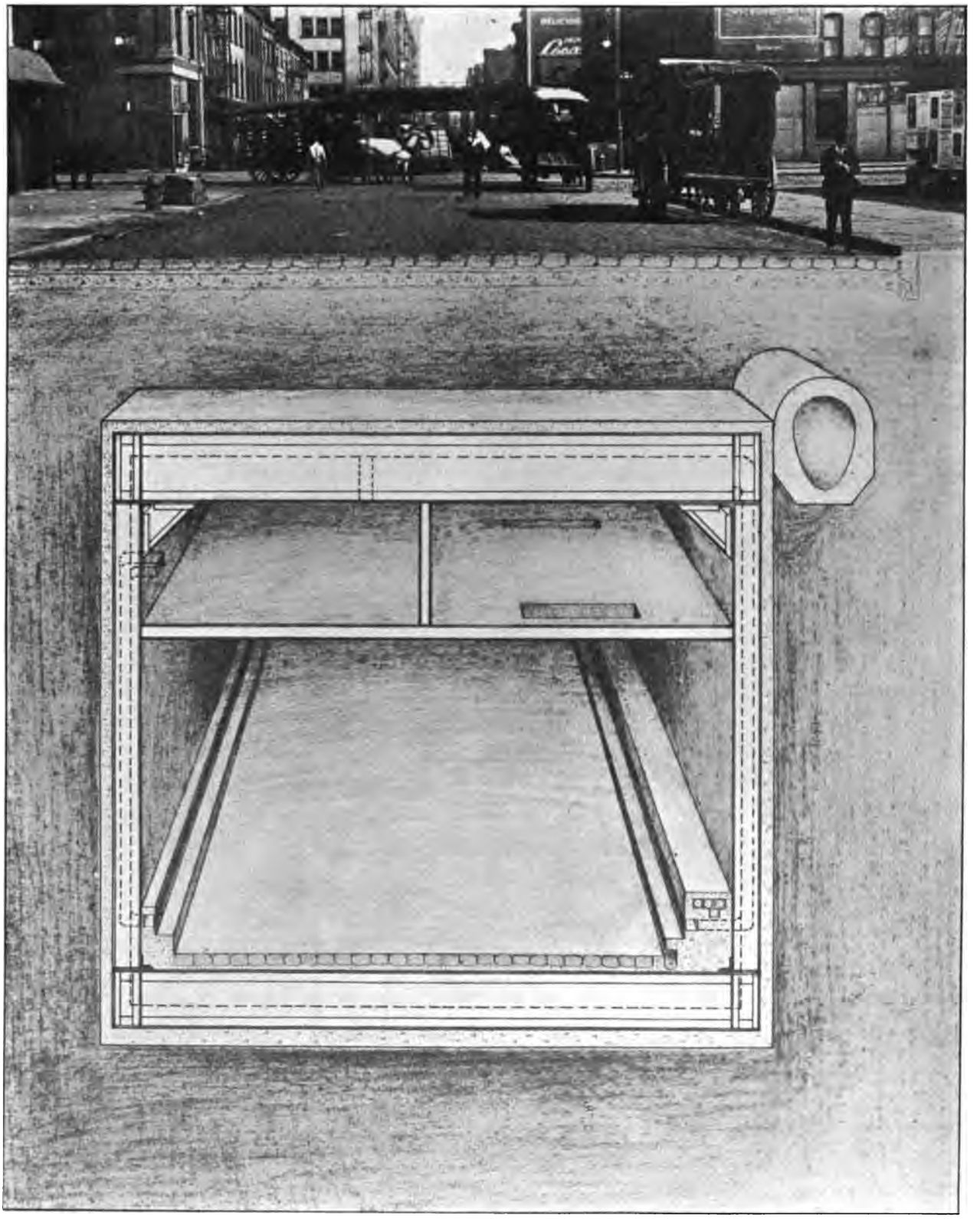
LIST OF PLATES

Plate No.	Subject
1.	Twin Cast Iron Tubes — Plan, Profile and Section.
2.	Tunnel Section in Canal Street near West Street, New York.
3.	Typical Approach Section with Air Ducts over Roadway.
4.	Typical Approach Section with Air Ducts at Side of Roadway.
5.	Sectional view at exit portal looking west on Canal Street.
6.	Section showing relation of Tubes to present piers — New York.
7.	Section showing relation of Tubes to Proposed Pier — New York.
8.	View of New York Land Shafts and Ventilation Equipment Building.
9.	Cast Iron Details — Heavy Section.
10.	Trench Tunnel — Steel Section.
11.	Count of Hudson River Marine Traffic.
12.	Schedule of Contracts.
13.	Location of New Jersey Approach looking east from Provost and 13th Streets.
14.	Canal Street Park, Site for Contractor's Plant.
15.	Changing Tracks and Subsurface Structures for Canal Street Shaft.



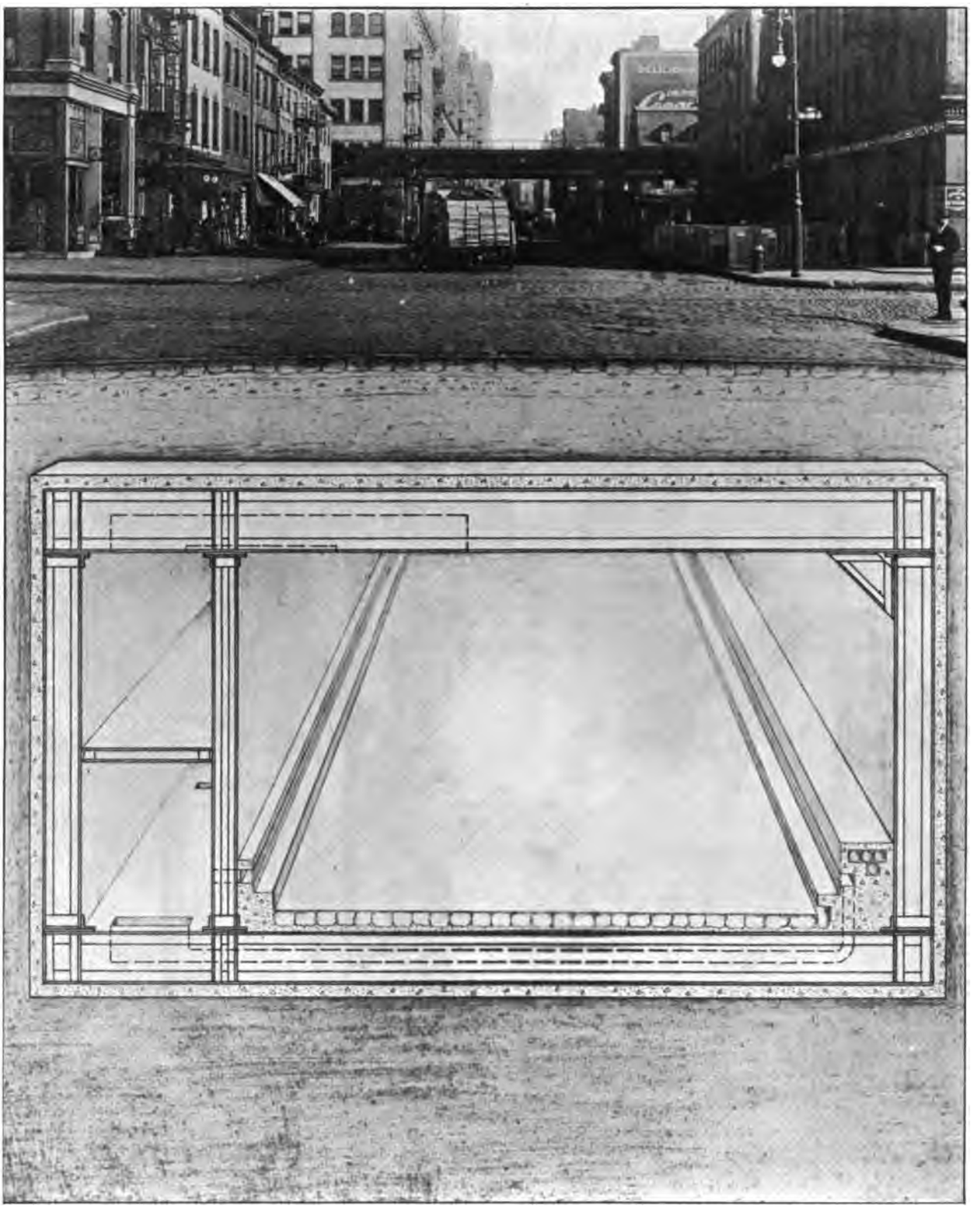
TUNNEL SECTION IN CANAL STREET NEAR WEST STREET, NEW YORK

Plate No. 2



TYPICAL APPROACH SECTION WITH AIR DUCTS OVER ROADWAY

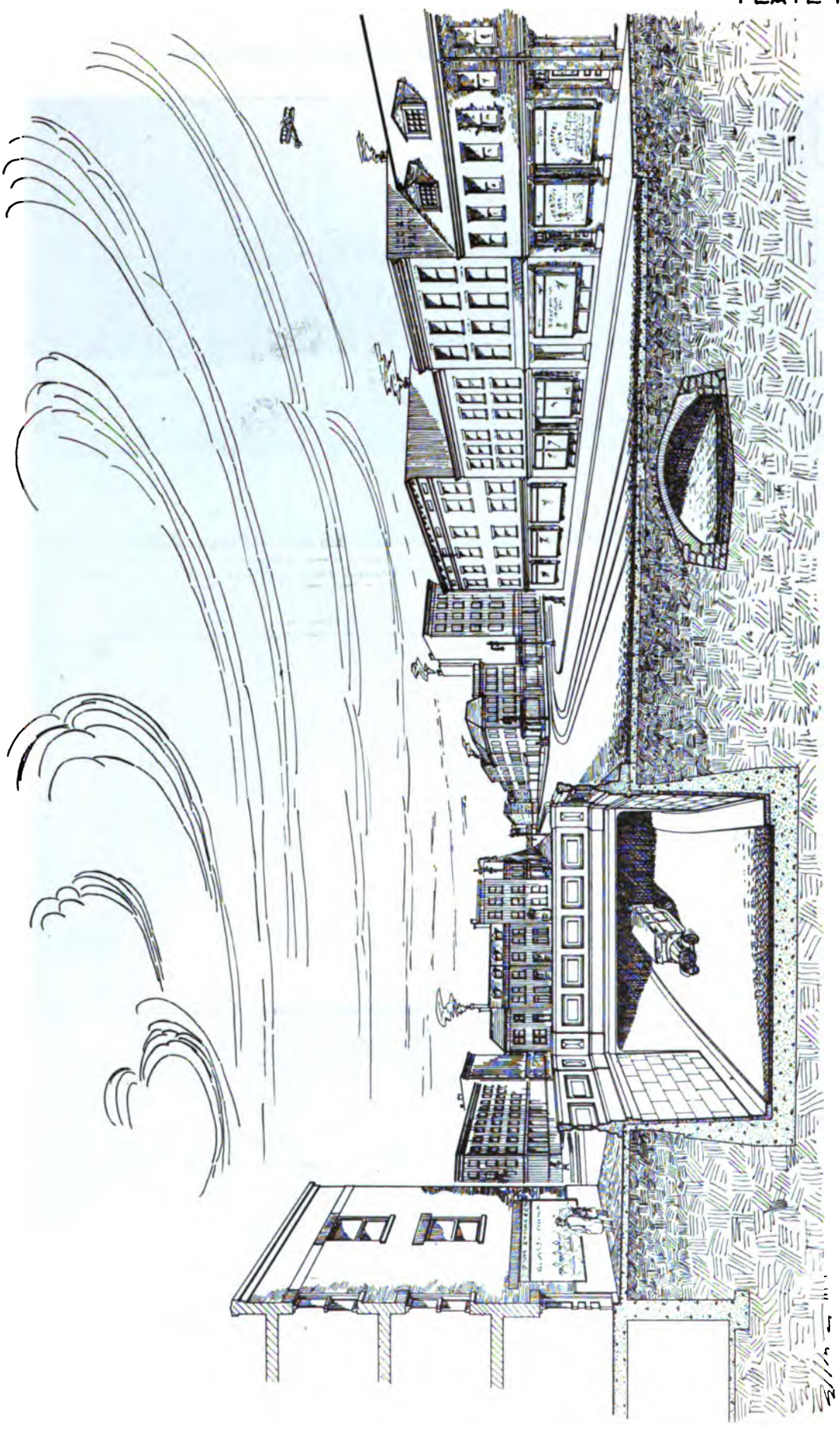
Plate No. 3



TYPICAL APPROACH SECTION WITH AIR DUCTS AT SIDE OF ROADWAY

Plate No. 4

PLATE NO. 5



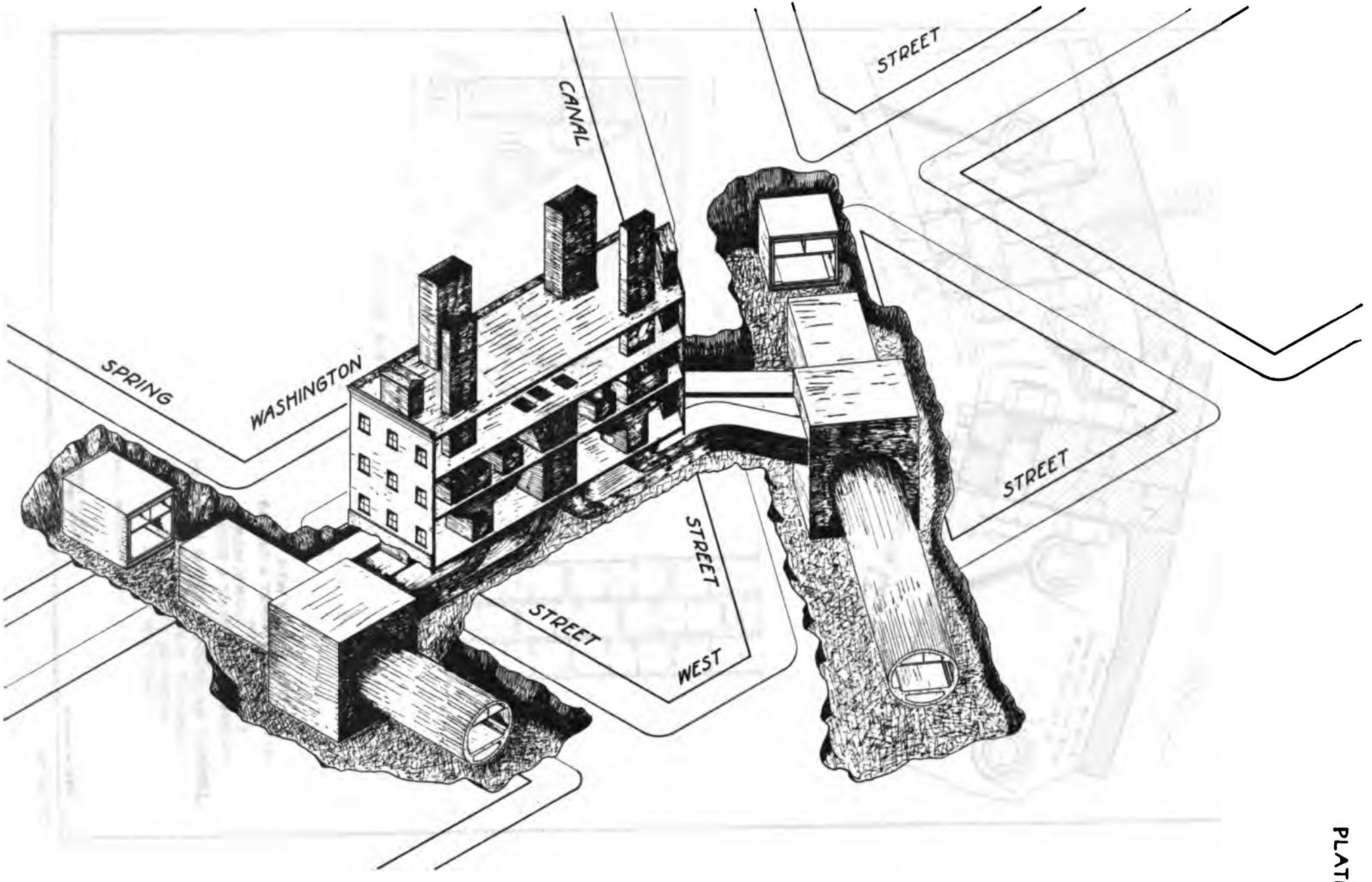
SECTIONAL VIEW AT EXIT PORTAL LOOKING WEST ON CANAL STREET

PLATE No 6

VENTILATION EQUIPMENT BUILDING.

PLATE No 7

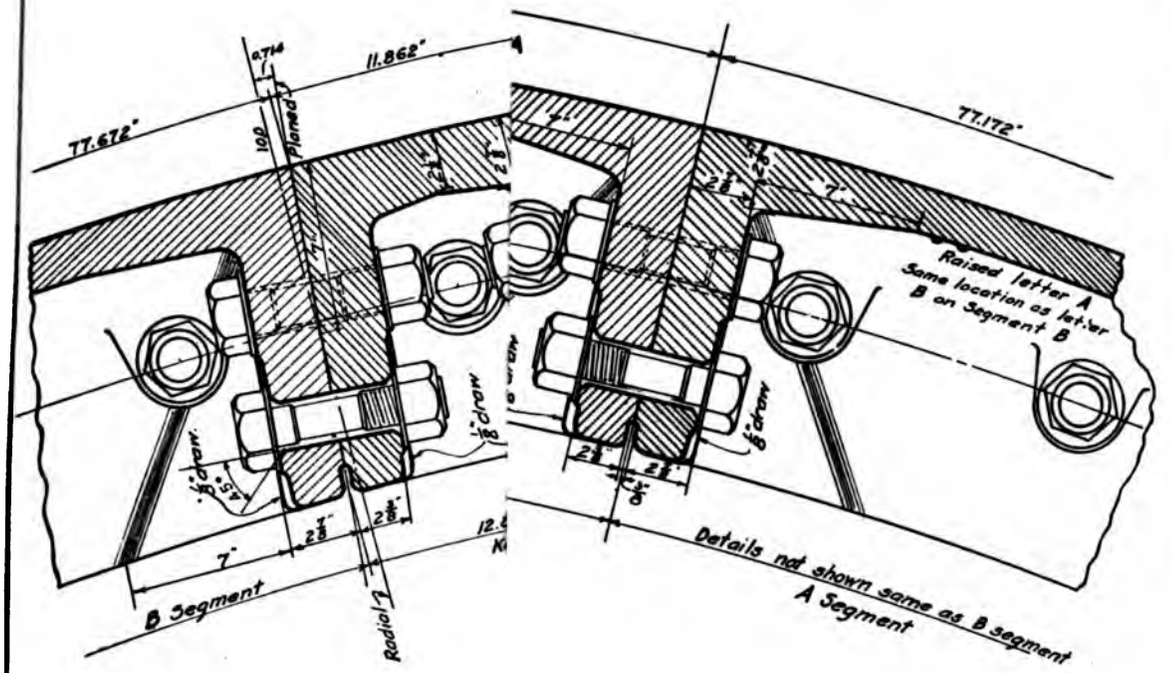
VENTILATION EQUIPMENT BUILDING.

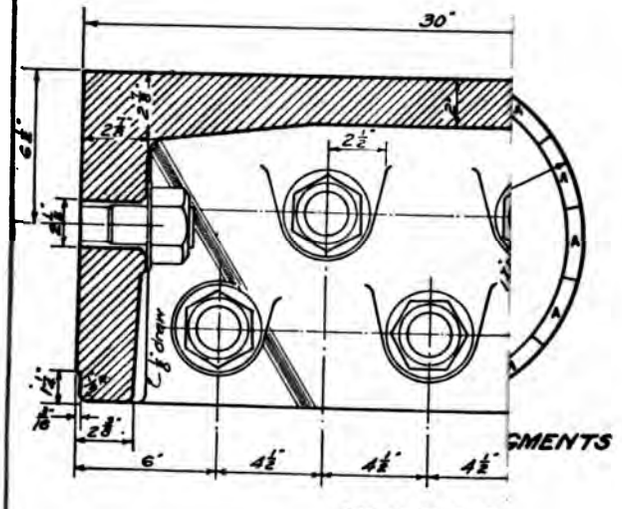


VIEW OF NEW YORK LAND SHAFTS
AND
VENTILATION EQUIPMENT BUILDING.

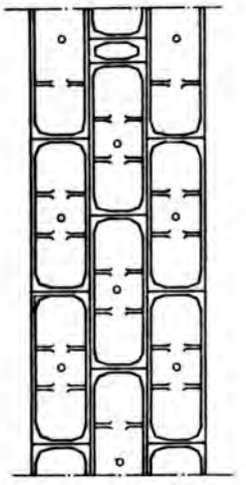
PLATE Nº 6

PLATE No. 9





SECTION A-A



SIDE VIEW

NEW YORK STATE
BRIDGE & TUNNEL COMMISSION
AND
NEW JERSEY INTERSTATE
BRIDGE & TUNNEL COMMISSION

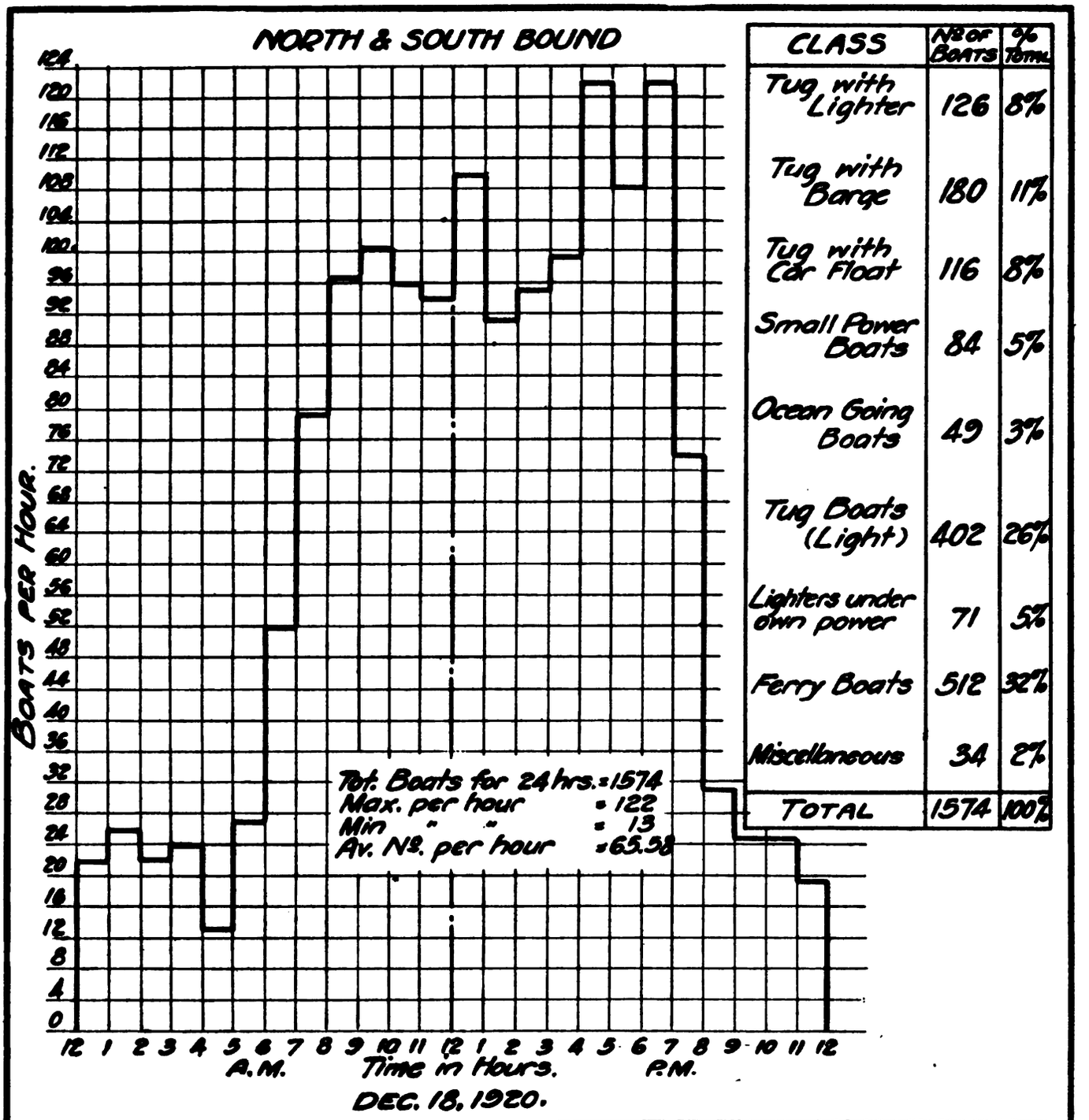
HUDSON RIVER VEHICULAR TUNNEL
29 FT. DIAMETER TUNNEL
CAST IRON DETAILS
HEAVY SECTION

SCALE: ____ INCHES

DRAWN BY J.H.D.
CHECKED BY O.F.B.
FILE NO. 7

DRAWING NO. 256

22"x32"=5°



CLASS	No. of Boats	% Total
Tug with Lighter	126	8%
Tug with Barge	180	11%
Tug with Car Float	116	8%
Small Power Boats	84	5%
Ocean Going Boats	49	3%
Tug Boats (Light)	402	26%
Lighters under own power	71	5%
Ferry Boats	512	32%
Miscellaneous	34	2%
TOTAL	1574	100%

NOTE:
Count made at location of tunnel.

NEW YORK STATE
BRIDGE & TUNNEL COMMISSION
AND
NEW JERSEY INTERSTATE
BRIDGE & TUNNEL COMMISSION

HUDSON RIVER VEHICULAR TUNNEL

COUNT OF HUDSON RIVER MARINE TRAFFIC

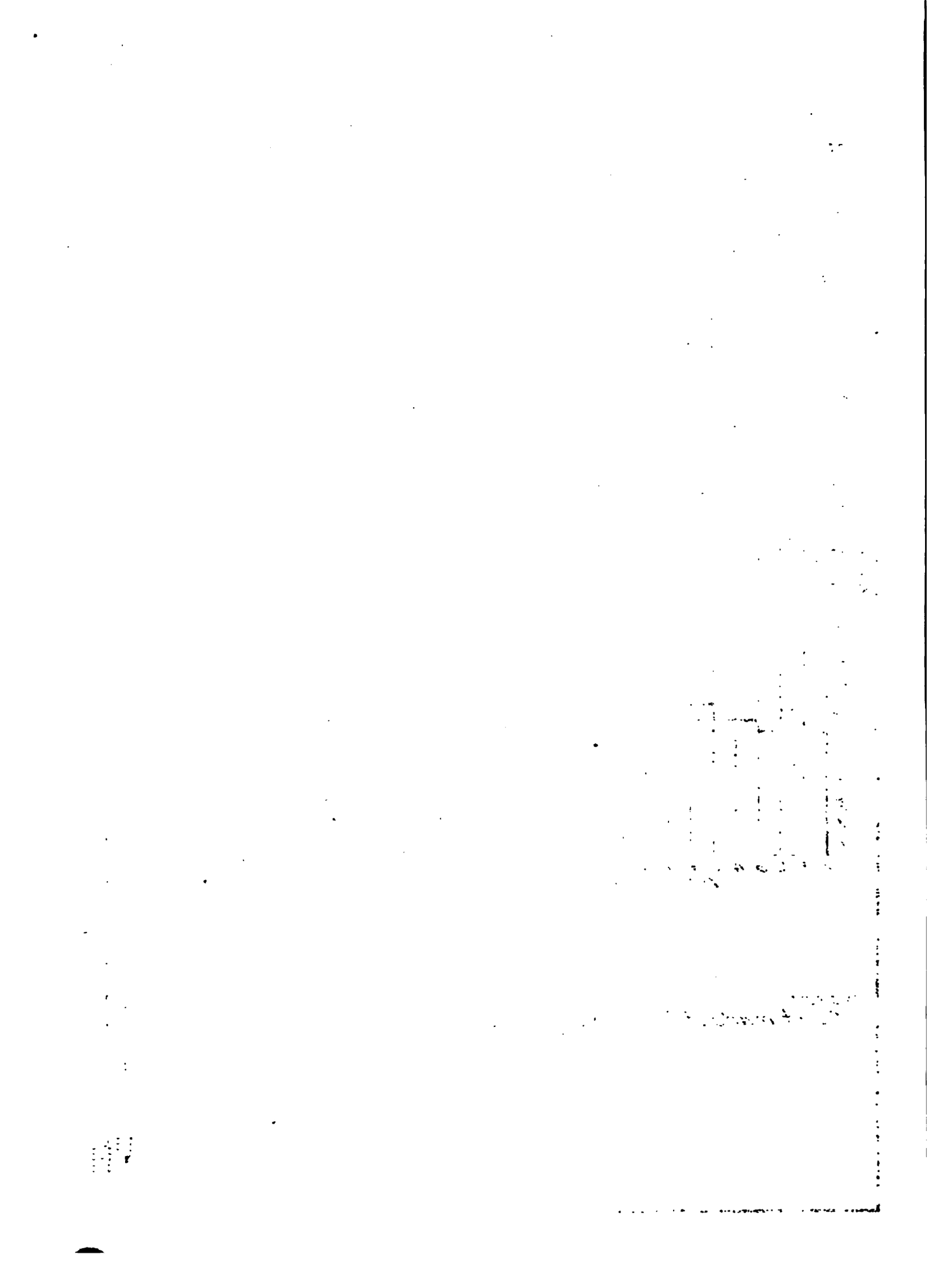


Plate No. 13

LOCATION OF NEW JERSEY APPROACH LOOKING EAST FROM PROVOST AND THIRTEENTH STREETS

CANAL STREET PARK, SITE FOR CONTRACTOR'S PLANT

Plate No. 14

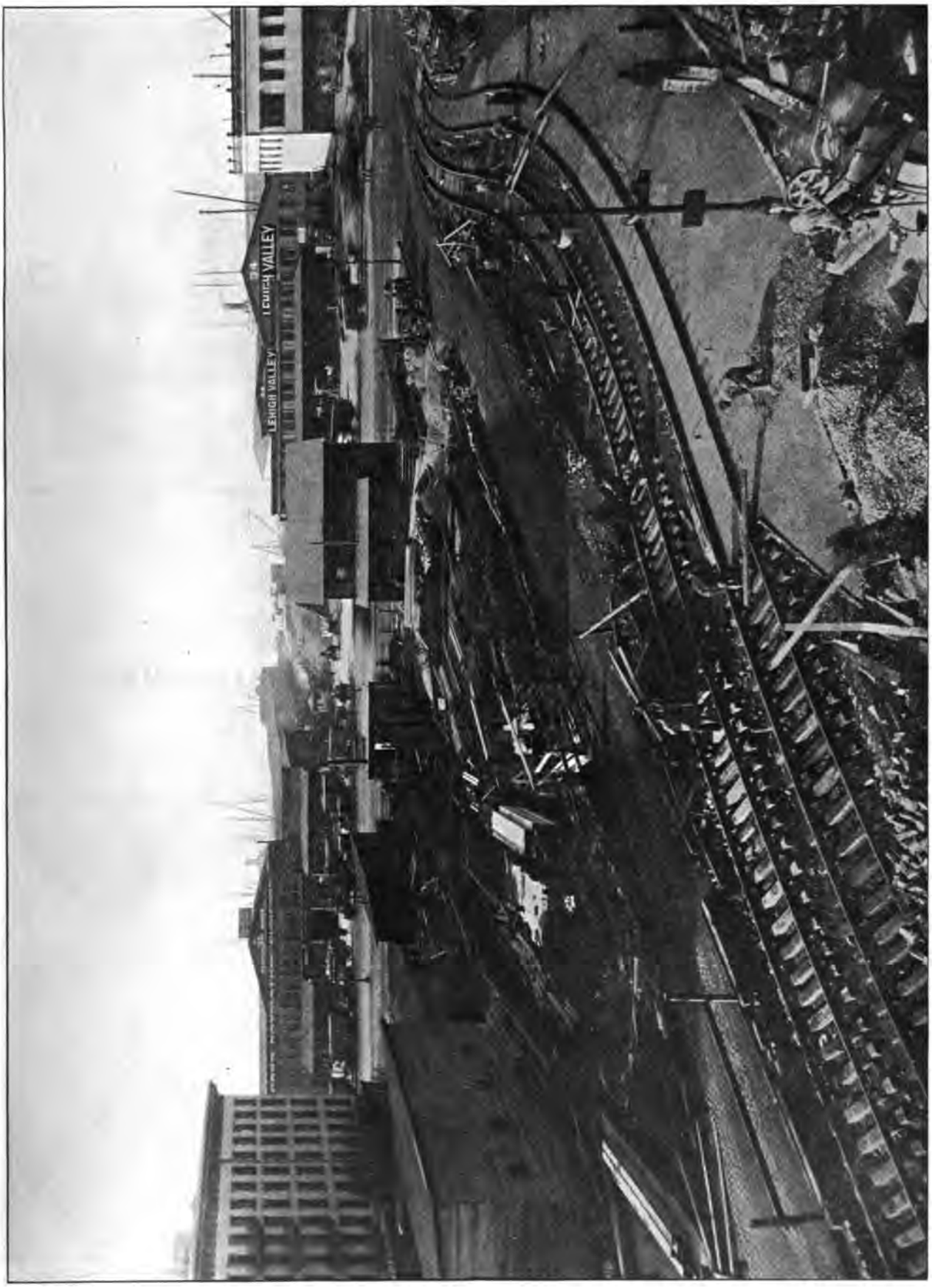


Plate No. 15

CHANGING TRACKS AND SUBSURFACE STRUCTURES FOR CANAL STREET SHAFT

APPENDIX NO. 1

RECOMMENDATIONS OF THE ADVISORY TRANSPORTATION ENGINEERING COMMITTEE

RECOMMENDATIONS OF THE ADVISORY TRANSPORTATION ENGINEERING COMMITTEE OF THE NEW YORK STATE BRIDGE AND TUNNEL COMMISSION AND NEW JERSEY INTERSTATE BRIDGE AND TUNNEL COMMISSION.

NEW YORK CITY,

November 17, 1920.

To MR. C. M. HOLLAND, *Chief Engineer*:

The first meeting of this committee was held at the Automobile Club of America on Thursday, July 8, 1920, Mr. H. J. Moran presiding. Various meetings have been held since that date. In the course of events Mr. H. J. Moran tendered his resignation as chairman and Mr. J. F. Winchester was appointed chairman to take up the work where Mr. Moran left off. Later on Mr. Winchester resigned and in your letter of October 28, 1920 the present chairman was appointed to continue the work.

At the meeting of July 8th you addressed the Committee giving a general outline of the work required of the Committee which work you later briefly outlined in seven questions. Each one of these questions was given thorough consideration by the committee at its various meetings and the report of the New York State Bridge and Tunnel Commission and especially your report of December 31, 1919 has been carefully studied and this committee feels that concurrence therein and approval thereof, as did the Board of Consulting Engineers, would be sufficient indication of their belief that the project has been properly worked out by you; but since you have requested it each one of these seven questions was given thorough consideration by the committee and the questions themselves, together with the Committee's recommendations, are set forth below:—

Also at a meeting of the Committee on July 22, 1920 it was decided to recommend a granite block pavement of the modern type, closely grouted, using Portland cement with expansion joints properly placed.

Question No. 1. What should be the minimum width of a two-line roadway in order to take care of traffic needs, keeping in mind the great cost which is involved with each six inches of roadway width, and the fact that any such excess would necessitate a larger tunnel, which introduces additional difficulties in construction and increased first cost, consequently making a continuing increased operating charge? The present cost of the project is estimated to be approximately $30,000,000, which is 2½ times that which was originally fixed for the project.

This Committee having in mind the great cost of each additional six inches of width of roadway and the fact that any such extended width would necessitate a larger tunnel which would introduce additional difficulties in construction and increase the first cost, resulting in continuously increased operating and maintenance charges, after a general discussion decided that they could get better ideas upon which to base their recommendations by observation on the Williamsburg Bridge during the rush hour from 5 to 6 p. m. and accordingly the committee agreed to meet on the Williamsburg Bridge at 5 p. m. on July 12th, which was done, and after observing two lines of traffic continuously for one hour the Committee recommends the adoption of Mr. Holland's plan for a twenty foot roadway. This Committee believes that the twenty foot roadway will provide sufficient clearance between vehicles to allow rapid progress of two lines of traffic. It is a fact recognized by this Committee that insufficient clearance between lines would slacken the speed of the lines but this would occur only when two vehicles of maximum width were abreast. Observation proves that, with the great variety of vehicle bodies in line, two of the maximum width are rarely abreast. The Committee does not believe there will be any appreciable effect upon

the speed of the lines on account of drivers operating in an enclosed structure with other vehicles near them, providing that each vehicle is required to remain in the line in which it starts, and we believe that strict rules should be made and enforced keeping slowly moving vehicles in one line.

The Committee decided that it was not necessary to make practical road tests with several motor trucks loaded, running the trucks in two lines because the observations from the Williamsburgh Bridge gave a most practical demonstration of what could be expected.

Question No. 2. What will be the ultimate size of the automobile truck? Is it not true that this will undoubtedly be fixed by a legal limit and become standardized, similar to railroad equipment in America today? In other words, will not the limitations imposed upon rolling equipment, due to layout of city streets in the past, prove the ultimate limiting factor? This does not mean that there will not be wide avenues, but how about all of the secondary streets which serve as feeders to the main arteries of travel?

The Committee is of the opinion that the ultimate size of the automobile truck — that is, its length, width and weight, will undoubtedly be fixed by legal limit and become standardized, similar to railroad equipment. Due to the layout of city streets in the past and the impossibility of widening all of them, it will be necessary to impose limitations upon rolling equipment and as a matter of fact this has already been done in many cities limiting the width to seven feet but even if the width of vehicles allowed to use the tunnel was fixed by the States of New York and New Jersey at eight feet, still a twenty foot roadway should give two feet operating clearance between, and one foot on each of the outer sides of the lines and the Committee considers this clearance sufficient.

Question No. 3. At approximately capacity operation, should not all vehicles be compelled to keep in the line in which they start?

The Committee believes that at capacity operation, all vehicles should be compelled to keep in the line in which they start, except that in case of stoppage by wreck or otherwise, if the stoppage could not be quickly moved, the police should allow vehicles in the stopped line to alternate with vehicles in the moving line and thus pass on through the tunnel.

Question No. 4. What provision, if any, beyond a center line marker, should there be made to keep vehicles in their respective lines? Should a crown be introduced, or should there be fixed boundaries such as grooveways or curbs?

The Committee is of the opinion that only a center line marker should be used to keep vehicles in their respective lines and that the police should enforce this rule. The Committee is of the opinion that a flat road surface should be provided and that there be no boundaries such as grooveways or curbs. This is a matter that has been carefully considered and our conclusions are that, if grooves or curbs were provided, serious delay would result in cases of stoppage of one line, or during the time of day when the tunnel is being used to its maximum capacity, the lines would be retarded by slowly moving vehicles if prevented by grooves or curbs from passing the slowly moving vehicles.

Question No. 5. What is the recommendation of your Committee in regard to the best method of taking care of disabled cars?

It is the opinion of the Committee that the best method of taking care of disabled cars would be by apparatus and removing disabled cars. The Committee has not lost sight of the fact that many heavily loaded vehicles will pass through the tunnel and that some of these very heavily loaded vehicles will break down; therefore, we believe that strong heavy wrecking wagons (motor driven), should be provided and they should be properly equipped with jacks, blocking dollies etc., so that if necessary, the broken down vehicle could be towed out of the tunnel, thus clearing the line. The Committee does not believe that any driver should be allowed to attempt to make a repair or adjustment or change any tire in the tunnel, if the operation would take longer than one minute, except during the times when travel through the tunnel is less than fifty per cent of capacity.

Question No. 6. What suggestions have your Committee in regard to the regulation of the movement of traffic, such as signal devices and police regulations?

We believe that the railroad system of signalling should be adopted. That is, when a stoppage occurs the nearest police officer should signal with a red light, if vehicles are required to come to full stop; yellow light, if required to proceed slowly; green light to indicate lines clear; and we believe these signalling devices should be so arranged that one line could be controlled independently of the other. We believe that sufficient police force should be employed to enforce rules adopted and that special attention should be given to vehicles entering the tunnel, so as to start slowly moving vehicles in one line, and the faster ones in the other line to the greatest possible degree, even though many more vehicles might be started in one line than another.

Question No. 7. What suggestion has your Committee as to the best method of cleaning the roadway of oils and gasoline drip, in order to have a safe roadway surface and eliminate the hazard of fire?

The Committee is of the opinion, the best method of cleaning the roadway of oil and gasoline would be the application of a liberal quantity of torpedo sand, which should be swept away by mechanical sweepers at least once in each twenty-four hours. The Committee is not in favor of having the roadway flushed with water as this would, on account of the grades, make the driveway hazardous when the roadway was wet, and of course the vehicles entering the tunnel from dry streets will not be prepared with chains to prevent skidding. Therefore, we believe dry cleaning is the proper method, and suggest that it may be necessary occasionally to apply an alkaline powder which with the torpedo sand would scour the surface of the pavement. The Committee is of the opinion that bank sand should be provided at frequent intervals along the driveway on each side, to be used when necessary to extinguish fire, and that soda-acid extinguishers of ten quart capacity should be supplied and located in convenient places along each side of each driveway, for further use in the extinguishing of fires and that fire hose with suitable reel and valves should be provided, the hose lengths to be sufficient to reach or lap one over the other and with sufficient capacity and water pressure to force a stream of water through a one-half inch nozzle at least fifty feet.

(Signed)

E. E. LASCHUM, *Chairman*
CHARLES S. LYON
E. C. WALKER
HENRY S. G. BROOKS
M. J. McDERMOTT
W. H. MOORE
P. V. V. TOBIN
B. K. RHOADS
I. A. HUNGERFORD
FRANK B. KURTZ
FREDERICK C. HORNER
C. G. PEPOON

The signers of the foregoing report are:

E. E. LASCHUM, Manager, Motor Vehicle Dept., American Railway Express Co.
P. V. V. TOBIN, Secretary, Howes Transfer and Contracting Co.
B. K. RHOADS, Asst. Superintendent, Motor Transport Dept., American Railway Express Co.
I. A. HUNGERFORD, Manager, Transport Department, Borden's Farm Products Co.
FRANK B. KURTZ, Manager, Truck Dept., Pierce-Arrow Motor Car Co.
FREDERICK C. HORNER, Engineer, Packard Motor Car Co.
C. G. PEPOON, Manager, Transport Dept., Tide Water Oil Co.
CHARLES S. LYON, Chief Engineer, Packard Motor Car Co.
E. C. WALKER, Superintendent of Motor Vehicles, William Farrell & Son, Inc.
HENRY S. G. BROOKS, Vice-President, Burns Bros. Coal Co.
M. J. McDERMOTT, Traffic Manager, James Butler, Inc.
W. H. MOORE, Manager, Garford Motor Truck Co.

APPENDIX NO. 2

CAST-IRON TUNNEL ANALYSES

ANALYSIS OF CAST-IRON TUNNEL SECTIONS

SECTION I

Subaqueous shield tunnel practice recognizes the uncertainty of absolute values of external loading, especially at the critical times during construction. The design of such structures is a development based upon past experience rather than a product of direct calculation as employed in ordinary structures. Consequently, a controlling consideration is the approach to a state of collapse during construction rather than the approach to the realization of the safe working stresses that might be employed in direct designing.

Preliminary Considerations.

Studies that are comparative, therefore, are possible and were made upon different sections of cast-iron tunnels, including sections proposed for the vehicular tunnel and sections of tunnels already built and in service, under similar conditions. The various results were placed upon what is believed to be a rational basis of comparison, through the different angles of repose assumed for the material forming the bed of the Hudson river. The investigations were carried through angles of repose ranging from three degrees to twenty degrees, which serve as an index common to all phases of the work. They also signify different relations of horizontal thrusts to vertical loadings, exterior to the tunnel. These relations are given in the curves of Drawing No. 254, File No. 7.

The resultants of the forces acting on the tunnel lining include the weight of the tunnel ring and of interior structural features together with compressed air within the tunnel and the exterior loads. The last named are least capable of precise definition, hence varying the exterior forces throughout a comprehensive range yields more conclusive results than confining the attention to any one given set of forces of doubtful value in themselves. These exterior forces represent active thrusts based upon Rankine's theory of earth pressure. The horizontal, abutting resistances of the surrounding material could be developed only through the deformation of the tunnel ring. This deformation develops internal stresses, all predicated upon the active thrusts. It is probable that stresses due to the active thrusts of the surrounding material at a given angle of repose may be found to equal the stresses due to the abutting power of the material at some other angle of repose. Therefore, for comparative purposes it is believed sufficient to base these studies upon active thrusts alone and thus preclude the uncertainties attaching to speculations as to what abutting resistances might be developed at a given angle of repose. At the same time approach is made to conditions admittedly more rigorous than those obtaining for the tunnel sections in their final state of completion, for the active thrusts provide a series of horizontal and vertical loads of increasing inequality that are more nearly representative of loads encountered during construction. So in these studies comparative values are emphasized rather than any consideration of the forces assumed for the exterior loading at any given angle of repose.

Conclusions were drawn, from comparisons of results which indicated the more favorable of alternative designs. Local points of weakness were developed and remedial measures devised.

Procedure.

The analysis comprised the determination of true equilibrium polygons for different conditions of loading whence the resultant thrusts and bending moments in the tunnel rings were completely determined. From these thrusts and moments, the stresses in the cast iron were directly computed, first, neglecting the effects of joints and bolts locally, that is, assuming a given ring to be continuous, acting alone and that its cross section is that of the corresponding segment design; second,

by means of supplementary analysis, including the effect of the joints and bolts under stress. The results were plotted as curves, in terms of the angles of repose, in both cases and conclusions drawn.

A statement of the procedure and conclusions illustrated by typical diagrams chosen from those of the analyses made upon the proposed twenty-nine foot diameter, cast-iron tunnel follows:

Method.

Equilibrium Polygons. The methods whereby the true equilibrium polygons were determined are two — the method of work, and that of deflection. Detailed explanations of these are contained in Section II. The advantage of the method of deflection is that it renders graphics unnecessary, thereby gaining in precision over the natural limitations of graphical analysis. The method of work, as here applied, consists of a graphical adaptation of the principle of least work, and, while generally satisfactory for ordinary purposes, lacked sufficient precision for low angles of repose, where percentage errors in scaling thrust eccentricities increased. Wherever both methods were used, the deflection method checked back most precisely upon results found independently by employing the principle of least work.

Joint and Bolt Stresses.

Supplementary analyses of the action of the bolts under stress and the modifications of stress resulting therefrom in the cast-iron of the segments were made. This portion of the analyses is described in detail in Section III. In general, the joint and bolt analysis consisted of investigations of the modifications of stress sustained by the cast-iron as caused by the action of the bolts in the end and circumferential flanges of a segment and, through the bolts in the latter, the effect of the two adjacent rings upon the given ring between them. The elasticity of the bolts, the bending of the short longitudinal flanges of the tunnel ring, the transfer of compression from the joint into the body of the segment, the tendency of a joint to open and the friction between the circumferential flanges enter into this part of the investigations. These calculations of bolt and joint stresses are also dependent upon the true equilibrium polygons, first determined.

Incidental Studies.

Approximation was also made as to the effect on the bending moments of the ring manifested by horizontal ties at the roof and floor of the driveway of the vehicular tunnel, twenty-nine feet in diameter.

Bolt hole clearances for tunnel ring being " out of round " were also estimated.

Principal Assumptions as to Loads, etc.

The cast-iron ring with entire internal structure, the cast-iron ring alone and the cast-iron ring subjected to compressed air within furnished three distinct cases for investigation. The concrete lining was considered only as contributing its dead weight.

One foot of tunnel length is the basis of computation. Thirty-eight feet of water upon thirty-one feet of silt are assumed to rest upon the top of the tunnel ring. Weight of water and silt, per cubic foot, are taken respectively at 64 pounds and 104 pounds. Air pressure at forty pounds per square inch for the twenty-nine foot diameter tunnel is applied. As before stated, calculations cover active pressures of silt (conjugate pressures by Rankine's theory) for angles of repose ranging from three degrees to twenty degrees.

As cohesion is neglected in Rankine's theory of a " granular mass ", vertical forces due to weights of tunnel ring alone and overlying material in some cases are less than the upward active pressures computed according to this theory. In such cases it appears, as noted on some of the diagrams, that a tendency towards a state of flotation of the structure would occur. Equalization of vertical forces for the sake of equilibrium is made by adding the necessary difference as a uniform,

overlying load, which may be considered as due to extra fill or as a tacit recognition of the existence of cohesion in the overlying mass.

Where the downward forces exceed the upward active pressures, the uniformly distributed difference to balance is applied upon the lower half of the structure. This additional set of forces may be considered as a partial development of the vertical abutting resistance of the material below the tunnel. In this case, the resulting upward reaction is found to lie between the values of the forces found by the active pressures and those that would result if the full abutting pressures could be developed, according to the theory.

Forty thousand pounds per square inch for steel bolts, with eighty thousand pounds per square inch for alloy steel bolts, are assumed for elastic limits, entering into the computations.

In all cases, the stresses have been computed for the so-called " heavy " section of segment, except for the stresses shown on Drawing 278 for the complete structure of the proposed " ordinary " section of twenty-nine foot tunnel.

The equilibrium, or funicular polygons for the twenty-nine foot diameter tunnel were derived for the ordinary section. It was found that the difference between the heavy and ordinary sections of the twenty-nine foot tunnel is such as to affect inappreciably the resulting bending moments and thrusts — a small fraction of one per cent — therefore, the stresses, calculated for its heavy section, were based upon the funicular polygons for its ordinary section.

The following listed twenty-five diagrams, taken from the studies made on the twenty-nine foot diameter tunnel, are typical of all and illustrate the procedure leading to the conclusions immediately following this list. These drawings appear in order at the end of this Appendix.

DIAGRAMS

The following drawings give the details of cast-iron segment, preliminary design for twenty-nine foot diameter tunnel:

File No. 7 Drawing No.	
134	Ordinary Section
135	Heavy Section

Force polygons and true funicular polygons for the twenty-nine foot diameter, cast-iron tunnel appear on the following sheets, and are given as typical of the groups from which they were chosen.

RING WITH COMPLETE INTERIOR STRUCTURE

File No. 7 Drawing No.	Angle of repose
164	3°
171	11° 18′
172	20°

RING ALONE AND WITH COMPRESSED AIR

File No. 7 Drawing No.	Angle of repose
175	3°
176	5°
178	11° 18′
179	20°

DIAGRAMS

Two of the three diagrams following were derived directly from the series from which the preceding typical drawings were taken, and neglect the effect of bolts, joints and action of rings adjacent to a tunnel ring in question:

File No. 7 Drawing No.	Title
245	Heavy section — crown, haunch and invert bending moments and effect of horizontal ties.
254	Ratios of horizontal to vertical pressures for different angles of repose.
278	Heavy and ordinary sections — maximum stress comparison.

The remaining drawings, following, taken also from the group representative of work on the twenty-nine foot tunnel, present the results of the bolt and joint stress analyses, culminating in No. 256 (Plate No. 9), the details of the revision of the cast-iron segment design of Sheet 135, denoted Revision " b."

File No. 7 Drawing No.	Title
256 (Plate No. 9)	Twenty-nine foot diameter tunnel, cast-iron details—heavy section (denoted Revision " b ").
261	Per cent stress variation with change in bolt position.
262	Per cent stress variation with change in total bolt tensions.
263	Per cent stress variation with change in end flange thickness.
264	Drift pin clearances.
267	Ring restrained by horizontal ties.
279	Twenty-nine foot cast-iron tunnel, heavy section, preliminary design and Revisions " a " and " b "; comparative stresses.

The concluding group, following, concerns the theoretical matters, exclusively.

File No. 7 Drawing No.	Title
269	Analysis by deflection method.
270	Analysis of joint stresses — Case I.
273	Analysis of joint stresses — formulae — Case I.
274	Analysis of joint stresses — Case II.
275	Analysis of joint stresses — formulae — Case II.
276	Analysis of joint stresses — Cases I and II — effect of circumferential bolts.

CONCLUSIONS AS TO DESIGN OF CAST-IRON SEGMENTS

In all that follows the terms " Outer," " Inner," " Without," and " Within " refer to directions in the circular tunnel cross-section, respectively from or towards its center.

(1) Governing Case.

Inspection of the funicular polygons of Drawings Nos. 164, 171 and 172 for example, show that the thrusts in the ring may be without or within the neutral axis of the ring, that is there may exist, besides direct thrusts in the ring, positive or negative bending moments. Two cases thus arise, denoted Case I, with thrust without and Case II with thrust within the neutral axis. Calculations indicate that Case I resulted in maximum stresses in tension and Case II, in compression, hence Case I usually governs.

(2) Joints.

The joint, as might be expected, is the weakest feature of the tunnel ring. Comparison of the stresses in the twenty-nine foot, C. I. segment, heavy section, preliminary design, with those for the same section, but with joints neglected, indicates the increase in stress due to the joints (Cf. Dr. Nos. 279 and 278). Hence, to strengthen the ring as a whole, there is necessary an increased strength of holding at the joints.

(3) Location of Critical Stress.

The critical stress in a segment is not in the joint itself; but immediately adjacent thereto, at the intersection of the circumferential flange of the tunnel ring. This stress is due to the combination of the normal bending stress in the segment's body, as this bending is modified by the circumferential bolt action, with the stress resulting from the local bending induced by the bolts of the end flange of the segment. These last bolts bind together the two successive segments of a ring at their ends.

(4) Tight Bolting.

The tighter a joint is bolted, the greater the strength of the joint, and consequently, the ring. Drawing No. 262 indicates that the greater the stress that the bolts can carry, as initial stress, i.e., in bolting operations, the greater the strength of the ring. Although a small increase in tension is apparent (due mainly to the circumferential bolts) in the body of the segment, where the tensions are usually lower than at the joint, this is inconsiderable when compared with the great decrease in stress in the critical part of the segment, the end flange, where the stresses are usually much higher.

Drawing No. 279 shows a similar effect obtained by utilizing the higher elastic limit of alloy steel bolts of one and three-quarter inches diameter, instead of that of ordinary steel.

The importance of keeping all bolts constantly tightened to their utmost strength, if possible, especially during construction when the tunnel ring receives its greatest punishment, is plainly manifest from these results alone, and suggests the desirability of tightening by means other than manual, if possible.

Finally, the advantage of changing to one and three-quarter inches alloy steel bolts is obvious. Plate No. 9 shows this design; but studies point to an advantageous further reduction in size of these alloy steel bolts.

(5) Location of End Flange Bolts.

The nearer the outer two bolts in the end flange of a " plate," or segment, approach the web and the two side bolts of the inner three approach the circumferential flanges, the greater will

be the reduction of local bending stresses, along with compression in the joint, induced in the metal at the joint. Drawing No. 261, File 7, indicates this reduction in the case of the inner bolts.

(6) Inutility of Middle End Flange Bolt.

The middle of the three inner bolts of the segment's end flange, Drawing No. 135, File No. 7, Section A-A, cannot act with its two adjacent bolts for, if the elasticity of the metal of the bolts and joints be considered at all, and consideration of their elastic deformations is the essence of these studies, the action of the two inner bolts adjacent to this middle bolt, puts the middle portion of the end flanges of the two abutting plates meeting at the joint into compression. There was found no possibility of a tension being induced in this bolt, other than the initial tension due to tightening bolts, unless the other bolts were stressed to failure, a condition that the middle bolt could never withstand. The only advantage apparent is its aid in process of tightening the other bolts, a practical consideration entirely, for it is plainly easier to tighten up three in line successively to and fro, than if there be but two bolts to work upon alternately. But as a factor contributing to the strength of the tunnel ring, the value of the middle bolt is nil.

This conclusion results from the detailed consideration of the analysis of bolt and joint stresses (Section III) but may be suggested by regarding the cross section of a segment, such as Section A-A of Drawing No. 135, (Cf. Drawing No. 270. File 7).

The tension transmitted through the joint from one segment of a ring to the next segment, will be largely transmitted through the bolts of the end flange The bolts nearest the " rim " of this cross-section, it is reasonable to suppose would take their stress first and even though stretching ever so little would act as fulcrums to the elastic metal of the end flanges abutting. The metal of each end flange in the vicinity of its middle inner bolt would therefore tend to move in the opposite direction to the stretch of the bolts, being on the opposite side of the bolt from the " rim " of the segment which is in tension. The metal of an end flange in the vicinity of this middle inner bolt, would therefore be pressed up against the metal of its abutting flange of the next segment. This segment's end flange would be acting in a similar manner, whence the compression existing as stated above.

Furthermore, it is of interest to note in the arrangement of end flange bolts in the segment of the Rotherhithe tunnel, that there are but two in the inner and three bolts in the outer line, near the web. Two were evidently found sufficient in number for the end flange inner bolts of that tunnel, though as a result of these studies, it would appear that they would have been more efficient if placed farther apart.

Three outer bolts near the web, appear more reasonable, from some of the considerations outlined, for the end flange metal is decidedly stiff close to the web and would behave more like a solid block of metal than an elastic plate; but on the other hand, if two bolts are sufficient in the inner position of the end flange, except for some such practical reason as previously cited, there is no reason why they should be increased in the outer position of the end flange.

In the sections submitted, the middle inner bolt was retained however, as it is thought its value in bolt tightening and leakage correction warrant its retention.

(7) Flanges Thickened at Corners as Well as Web of Segment.

To strengthen the segment locally (C.f. conclusion No. 2 above) it is further concluded that the metal of the flanges, inside, at the corners of the segment should be thickened as shown on Plate No. 9. This thickening is consistent with the web thickening of earlier designs for about seven inches adjoining the flanges. The comparative value of this local flange thickening is brought out in Drawing No. 263, File No. 7, where the end flange is thickened one-quarter of an inch.

Diagram Assembling Results.

Drawing No. 279 shows the effects of all changes in design details upon the twenty-nine foot, cast-iron heavy section (Drawing No. 135) resulting in the section of segment design designated

Revision "b" (Plate No. 9). Compare the curves of Drawing No. 279 denoted "preliminary design" and "Revision 'b' segment."

Segment Design.

Pursuant to the foregoing conclusions, the preliminary design of segment for cast-iron tunnel twenty-nine feet in diameter, as given on drawing No. 135, File No. 7, was carefully studied, especially with regard to the effect on clearances, of changing the location of bolts, of enlarging them and of locally thickening the metal. The length and number of segments were also dependent upon these considerations through the appropriate size of key. Corresponding clearances also were studied in this connection and compared for key and segment as occurring in the segments of the following tunnels already constructed:

Heavy and ordinary sections of Pennsylvania R. R. tunnels and of Route 48 and Route 8, Public Service Commission of the First District.

A first revision, denoted Revision "a," was tentatively made by increasing the bolts from one and three-quarter inches to two and one-quarter inches (shank diameters) ordinary steel and thickening the flanges at the corners as shown in Plate No. 9, for Revision "b," the second revision.

This second revision, Revision "b," substituted bolts of a steel of high tensile strength and elastic limit, such as Vanadium steel. It permits the use of bolts of one and three-quarter inches diameter and probably less. Revision "b," more than "a," betters stress conditions generally with added advantages of ample clearances with more favorable bolt location and greater ability to tighten the bolts. The metal at the flange corners is thickened as shown.

Drifting Bolt Hole.

For an assumption of a twenty-nine foot diameter circle becoming "out of round," by its vertical diameter decreasing, say by three inches and its horizontal diameter increasing a like amount, the amount of drifting to make the end bolt hole of a circular segment coincide with the corresponding bolt hole of the above resulting elliptical segment, has been estimated. On Drawing No. 264, Fig. No. 1, these variations and the clearances for entering drift pin are shown completely in sixty-fourths of an inch.

Although an appreciable saving in weight of metal is obtained due to the elimination of a longitudinal flange per ring, it is not considered practicable so to decrease the number of segments that the length of a segment becomes unwieldy. The number of segments in Revision "a" was twelve and a key. This reduction from fourteen of the design shown on Drawing No. 135 is necessitated by an increase in the size of key. Increase in size of the key follows the increase in bolt diameter to two and one-quarter inches to maintain workable clearances, but with Revision "b," in the smaller bolts, a greater number of segments is possible.

Ordinary Section.

Attention should be drawn here to the curves of Drawing No. 278.

All of the comparative studies made show conclusively that Revision "b" of the twenty-nine foot diameter tunnel is adequate. Drawing No. 278 indicates the close relation of the preliminary design of the heavy section with its ordinary section neglecting bolts and joints.

It is therefore probable that further study of this ordinary section of the twenty-nine foot, cast-iron tunnel will result in appropriate modifications in detail, such as here described for the heavy section, and that there would thereby be obtained a cast-iron lining, acceptable, fully adequate, and certainly most economical.

Conclusions from Analysis.

The following conclusions are drawn from the analyses made and shown upon the diagrams (Cf. Drawing 278):

1. Unit stresses, both in compression and tension, are greater for the entire structure than for the ring alone or for the ring subjected to compressed air.

2. For the ring with compressed air, the compression values are less than for the ring alone, while the tensile values are greater.

3. Air pressure of forty pounds per square inch produces a uniform tension in the tunnel ring of 1757 pounds per square inch for the twenty-nine foot tunnel. This decreases compressive stresses and increases tensile stresses accordingly (Cf. Drawings Nos. 175 to 179).

Effect on Horizontal and Vertical Diameter.

4. For the entire structure at all angles of repose above 3°, the funicular polygons show that the vertical diameter of the tunnel tends to decrease and the horizontal diameter to increase; but Drawing No. 245 indicates that below two degrees, for the twenty-nine foot diameter tunnel, the reverse would appear to be true. (For a twenty-three foot diameter tunnel the point of change was in the region of one and one-half degrees while for a forty-two foot diameter tunnel it was found as high as about four and one-half degrees.)

5. For the ring alone and for the ring with compressed air for three degrees, as calculated, the tendency is to lower the crown and the invert and coincidently to shorten the horizontal diameter slightly. In this connection it is interesting to note that the equilibrium polygon crosses the neutral axis at three points between crown and invert, thereby indicating the probability of compensation of these deformations in a given direction.

6. For higher angles of repose the ring alone and ring with compressed air exhibit a decrease of the vertical and increase of the horizontal diameter.

It is to be remembered that the bending moments for the ring are unchanged by the application of the compressed air condition, the thrusts undergoing considerable alterations therefrom, whereby the stresses are affected.

Diagrams Nos. 261, 262 and 263 contain the results of preliminary studies that indicate the relative effect of the changes in bolt position and strength and flange thickness and are self-explanatory.

Restrained Bending Due to Horizontal Ties.

Drawing No. 267 gives expressions for a twenty-nine foot diameter ring, whereby bending moments under uniform vertical loading may be calculated and for ring unrestrained and restrained by ties, as shown. It is the basis for calculation of curve M_t' of Drawing No. 245, File No. 7. It is an approximation whereby the bending moments shown on Drawing No. 245, for the haunch, were inserted in expression for Case I, M_b of Drawing No. 267 and solution for corresponding uniform load, p, to produce this moment, computed for an elastic ring. This vertical load of uniform intensity, p, resulting was then introduced into Case II, and M_t' directly solved. The relative values of moment M_t' indicate the effect of the floor of the upper air duct and of the roadway if constructed so as to serve as ties. The moments are seen to be reduced thereby to about one-third their values. This feature, if properly installed, can be counted an added factor of safety in the vehicular tunnel.

SECTION II

The two methods of analysis followed in the investigations described in Section I are:

1. The Method of Work.
2. The Method of Deflection.

Each will be outlined.

THE METHOD OF WORK

A graphic adaptation of the principle of Least Work was used in the tunnel analyses to establish the true equilibrium, or funicular polygons from the systems of loadings assumed.

The procedure is simple, consisting of first drawing the force polygon in the usual way, then assuming several pole distances, drawing for each a series of equilibrium polygons. For each pole distance, or crown thrust, there then results a series of equilibrium polygons each having a different point of application of the thrust at the crown.

The normal thrust and its eccentricity at each joint is then obtained for each polygon, whence the resulting moment is calculable. The squares of these moments and corresponding joint thrusts are then tabulated and the square of each moment is divided by the moment of inertia of the ring cross-section and the square of each thrust by the corresponding cross-sectional area of the ring. (These are the factors entering into the expression for internal work due to flexure and direct stress in the ring.)

Equation No. 2 below given embodies the substance of this last explanation and is derived as follows:

The analytical expression for internal work, w, may be written as follows:

$$w = \int \frac{M^2\,dl}{2\,E\,I} + \int \frac{P^2\,dl}{2\,E\,A} \qquad (1)$$

in which

w = Internal work.
M = Bending moment.
P = Normal thrust on joint.
dl = Differential length of neutral axis of ring.
E = Modulus of elasticity.
I = Moment of inertia of cross-section (radial section of ring) at which the moment M and thrust P occur.
A = Area of the cross-section.

As only relative and not absolute values of the work are required to establish a minimum the factors entering as variables need only be considered thereby greatly simplifying the procedure. If constant lengths sufficiently small be taken along the neutral axis we may write for a value, w^1, representative of the work as follows:

$$w^1 = \sum \left(12\,\frac{P^2 n^3}{h^3} + \frac{P^2}{h} \right) \qquad (2)$$

P = Normal thrust as before.
n = Distance from point of application of P to middle of joint.
h = Thickness of ring. (if of rectangular cross-section)

The above results are tabulated for the different joints and summed for each polygon, for each thrust. The resulting sums are representative of the internal work of resistance for each case.

The minimum value, obtained graphically also, indicates directly the true thrust and its point of application at the crown whence the final or true equilibrium polygon follows. But the limitations of graphic work, especially for the low angles of repose where large percentage errors result in scaling the small eccentricities, soon became apparent and affected comparative values in an appreciable manner. The results were as satisfactory as could be desired for ordinary purposes, however.

A complete, but simply devised method that would be analytic throughout was therefore sought and the method based upon the principles of deflection developed. This is described as follows:

THE METHOD OF DEFLECTION

1. General Considerations.

Figure 2 and Figure 3 of Drawing No. 269, File 7, represent a linear elastic ring, subjected to a system of loads such as diagrammed in Figure 1A. This ring is assumed to be symmetrically loaded with respect to its vertical diameter a – d of Figure 1A.

The derivation of the theoretical features of this method depend in effect upon the following:

As the loading is symmetrical, the tangent at d, Figure 1A, remains throughout horizontal. If the ring be cut at the crown (Figure 3) it will deflect, as shown, through an angular deflection ϕ' and a linear horizontal deflection, Δ'.

The restoration of the original integrity of the ring may be effected by ascertaining the proper combination of horizontal crown thrust and moment at the crown, to neutralize the angle ϕ', which represents the entire angular deflection of the half ring, shown in full line, and the deflection, Δ'.

The vertical component of the deflection need not be considered as the horizontal deflection and angular deflection at the crown furnish the necessary equations of condition, due to the symmetry, above noted.

From the symmetry of the ring and its loading, the right half, say, may be considered a curved cantilever as shown in the figures of Drawing No. 269, File 7.

With the determination of the crown thrust and moment, all other thrusts and moments in the ring follow:

This method neglects the direct strain in the ring due to the component of the thrusts normal to a " joint," also shearing strains in the ring are neglected. These factors were found to be negligible in the least work analyses that had been previously carried on.

II. Details of Method:

Preliminary to an analysis, the ring is subdivided into voussoirs of equal length and the resultant voussoir load is determined, including both external and internal loads or pressures.

These are usually calculated but for the sake of explanation, are indicated in the diagrams, Figures 1 and 1A of Drawing No. 269. The force polygon O – AB–BC, etc. is drawn, whence, for a cantilever, with crown thrust zero, the pole of the equilibrium polygon will be at O, Figure 1, and the resulting equilibrium polygon will be $b^1 - c^1 - d^1 -$, Figure 1A.

All values are for unit length of tunnel. ϕ' is expressed in radians and the loadings include both internal weights and pressures and external earth pressures, but the crown thrust and moment are excluded.

All forces and distances are considered positive; clockwise moments positive; counter-clockwise, negative; bending moments positive when causing compression in extrados; linear crown deflections positive to right, and angular deflections positive clockwise.

Considering the semi-ring now as a linear cantilever beam concentrated at the neutral axis and fixed at the invert and taking the voussoir joint " cd " as typical for purposes of illustration, let:

Y_{cd}	Distance of joint CD below crown.
M_a	Crown moment.
M_{cd}	Bending moment at CD (actual).
M'_{cd}	Moment about CD of all *loading* above CD, i.e., the *bending moment* at CD due to the loading only (excluding crown thrust and crown moment).
M_{1cd}	Bending moment which would be produced at CD by a unit thrust at the crown.
M_{2cd}	Bending moment which would be produced at CD by a unit moment at the crown.
T_a	Crown thrust.
T_{cd}	Thrust at joint CD.
T'_{cd}	Resultant of all loading above CD.
Δ'	Horizontal linear deflection at the crown due to loading only.
Δ_1	Horizontal linear deflection at the crown due to a unit crown thrust.
Δ_2	Horizontal linear deflection at the crown due to a unit crown moment.
ϕ'	Angular crown deflection due to loading.
ϕ_1	Angular crown deflection due to unit crown thrust.
ϕ_2	Angular crown deflection due to unit crown moment.
n	Number of voussoirs.
l	Length of voussoir along neutral axis.
E	Modulus of elasticity of material.
I	Moment of inertia.

2. Computation of Δ' and ϕ'.

Draw a funicular polygon for zero thrust and moment at the crown. This is accomplished by locating pole at point O (Figure 1).

Then $M'_{cd} = T'_{cd} \times \overline{cd - c''d''}$

(Fig. 1) (Fig. 2)

Deflections at the crown due to

M'_{cd} are $\Delta_{cd} = \frac{1}{EI} M'_{cd} Y_{cd}$ and $\phi'_{cd} = \frac{1}{EI} M'_{cd}$,

Note, however, that $M'_a = 0 \therefore \Delta'_2 = \phi'_a = 0$ also that $\Delta'_d = \frac{1}{2EI} M'_d Y_d$ and $\phi'_d = \frac{1}{2EI} M'_d$

(The 2 appears in the denominator because M'_d applies only to half a voussoir).

From the above it is evident that

$$\Delta' = \frac{1}{EI}\left[\Sigma M'Y - \frac{M'_d Y_d}{2}\right]$$

$$\phi' = \frac{1}{EI}\left[\Sigma M' - \frac{M'_d}{2}\right]$$

The computation may best be arranged in tabular form.

When $\Sigma M'Y$ & $\Sigma M'$ have been obtained by footing the appropriate columns, deduct from each one-half the last figure in the column from which it was obtained. The funicular polygon b'c'd' can best be checked by computing M'_d analytically and comparing with $-T'_d \times \overline{d-d''}$

3. Computation of Δ_1, Δ_2; ϕ_1, ϕ_2.

Δ_1 & ϕ_1.... In this case $M_{1cd} = Y_{cd}$

$\therefore \Delta_{1cd} = \frac{1}{EI} Y^2_{cd}$ and $\phi_{1cd} = \frac{1}{EI} Y_{cd}$

As before $\Delta_{1a} = \phi_{1a} = 0$; $\Delta_{1d} = \frac{1}{2EI} Y^2_d$; $\phi_{1d} = \frac{1}{2EI} Y_d$

$$\therefore \Delta_1 = \frac{1}{EI}\left[\Sigma Y^2 - \frac{Y^2_d}{2}\right]; \quad \phi_1 = \frac{1}{EI}\left[\Sigma Y - \frac{Y_d}{2}\right]$$

Δ_2 and ϕ_2 In this case $M_{2cd} = 1$:

$\therefore \Delta_{2cd} = \frac{1}{EI} Y_{cd}$ and $\phi_{2cd} = \frac{1}{EI}$

Note that:

$M_{2a} = 1 \quad Y_a = 0 \quad \Delta_{2a} = 0$ but $\phi_{2a} = \frac{1}{2EI}$

As above, $\Delta_{2d} = \frac{1}{2E_1} Y_d$; $\phi_{2d} = \frac{1}{2EI}$

$$\therefore \Delta_2 = \frac{1}{EI}\left[\Sigma Y - \frac{Y_d}{2}\right]; \ \phi_2 = \frac{1}{EI}\left[n - 1 + \frac{1}{2} + \frac{1}{2}\right] = \frac{nl}{EI}$$

Work is best carried out analytically in tabular form.

4. Computation of T_a and M_a

Since T_a and M_a acting in combination must neutralize the deflections Δ' and ϕ', we may write:

$T_a\Delta_1 + M_a\Delta_2 = -\Delta'$ ..... (1)

$T_a\phi_1 + M_a\phi_2 = -\phi'$ ..... (2)

From (2), $T_a = \frac{-\phi' - M_a\phi_2}{\phi_1}$ ..... (3)

Substituting in (1) and solving for M_a,—$M_a = \frac{-\Delta_1\phi' + \Delta'\phi_1}{\Delta_1\phi_2 - \Delta_2\phi_1}$ * ..... (4)

Substituting in (3) and solving for T_a, $T_a = \frac{-\Delta'\phi_2 + \Delta_2\phi'}{\Delta_1\phi_2 - \Delta_2\phi_1}$ * ..... (5)

To obtain the actual bending moment at any joint as " cd " we may write:

$$M_{cd} = M'_{cd} + M_a + \overline{T_a \times Y_{cd}}$$

* Note that Δ' and ϕ' are negative for all actual loadings.

SECTION III

ANALYSIS OF BOLT AND JOINT STRESSES

General Considerations:

Recognition of the bolted joints in the cast-iron lining requires consideration, not only of the bolt stresses but also of the modification which the jointed character of the lining introduces into the stresses in the cast-iron itself.

Due to the action of the circumferential bolts, these modifications are not confined to the immediate vicinity of the joint; but extend throughout the length of the segment, or lining "plate" as it is often called. The greatest effects are found at the joints or in the centers of the segment lengths.

The stresses occurring at the center of the segment which include the effects of bolts and joints have been denoted, "Tension, (or compression) in body of segment," while those at the ends of a segment, that is, near or at its end flanges, have been designated as stresses "at the joint." Shearing stresses have been found too small to be considered.

Joints.

The analysis is divided into two main parts, in which consideration is had of the effects of:

(1) End joints of segment (Longitudinal joints of tunnel)

(2) Circumferential joints.

Each of these is treated again under two cases, viz.—

Cases I and II

Case I — Where the center of pressure in the ring is outside of the center of gravity of the section, causing the joint to tend to open at the intrados.

Case II — Where the center of pressure is inside the center of gravity, causing a tendency for the joint to open at the extrados.

CASE I

In connection with the following, compare Drawing Number 270, File Number 7 and Nomenclature for Case I.

JOINT AND BOLT ANALYSIS NOMENCLATURE

Compression in Extrados

Note: *Inner* = *Towards; Outer* = *Away* from center of circular tunnel.

A	Area of radial cross-section of segment.
A_b	Area of bolt.
$I_{c.g.}$	Distance from center of gravity of cross-section to outside face of segment.
l_v	Length of segment.
U	Width of segment (parallel to axis of tunnel).
W	Thickness of web.
W_1	Thickness of end flange of segment on C.L. of inner bolts, (end flange = longitudinal flange of tunnel)
l_b	Distance from C.L. of inner bolts to outer face of segment.
l_1	Twice the edge distance of inner bolts = width of portion of end flange assumed to act as a fixed ended beam.
l_2	Distance end bolts of inside line to face of nearest main or circumferential flange.
l_3	Distance between end bolts of inside bolt line.
l_p	Distance of line of pressure from outside face of segment: l_p is + when line of pressure falls within the ring; l_p is — when line of pressure falls outside the ring.
l_{n_1}	Distance from neutral axis of body of segment to outside face.

l_n Distance from lowest point of contact of abutting segments to outside face.

λ The ratio (dist. from face of joint to point where bending becomes normal) ÷ (semi length of segment).

e Distance from center of end bolt (inner row) to point where contact of end flanges begins.

Δ_1 One-half maximum opening between end flanges of abutting segments measured on C.L. of inner line of bolts.

Θ One-half the angle between faces of end flanges of abutting segments.

l'_p Distance from P′ to outside face of segment.

I Moment of inertia of cross-section of segment.

I_1 Moment of inertia of fixed ended beam formed by end flange $= \frac{l_1 w_1^3}{12}$

l_B Semi-length of bolt " B."

Δ_B Semi-elongation of bolt " B."

P Resultant thrust in ring.

C_j Total compression near outside of joint.

T Total net tension transmitted from ends of end flange to main flanges of segment.

M Bending moment in body of segment.

t_b Total initial stress in each of bolts " B. "

t'_b Total final stress in each of bolts " B."

k_{m_1}, k_{m_2}, k_{m_3} Extreme fiber stress due to M_1, M_2, M_3, respectively.

M_1 Bending moment at each end of end flange = maximum bending moment in portion l_2 of end flange.

M_2 Bending moment at end bolts (= maximum in portion l_2 of end flange).

E_c Modulus of elasticity of cast iron in compression.

E_s Modulus of elasticity of steel in tension.

G Modulus of elasticity of cast iron n shear.

P′ Resultant of P and effect of circumferential bolts.

M_3 Bending moment at center of end flange. (Occurs only in Case C)

k_1 Extreme fiber stress in body of segment (compression).

k Extreme compressive stress in joint, minus k_1.

Note 2: Corresponding to P′ and l'_p will be new values, l'_{n_1}, M′, k'_1 of l_{n_1}, M, k_1.

Longitudinal Joints (or end joints of segment)

The flexure of the end flange of a segment and the stretching of its bolts permit a joint to open more or less, and consequently, the stresses in the abutting cast iron segments and the steel bolts are modified. These modifications are thus explained:

(a) The area of compressive stress (represented by l_n, Drawing Number 270) diminishes, causing a nearly proportionate increase in this intensity of stress.

(b) The " pull " (t'_b) of the bolt on the end flange induces bending moments (M_1 and M_2) in this flange and in the portion of the circumferential flanges immediately adjacent to its ends.

Middle bolt.

(c) This flexure of the end flange under the action of its bolts being equal and opposite to the flexure in the end flange abutting against it, places the two abutting flanges in compression, with relation to each other, in the region between their end bolts (B) thereby rendering the middle bolt of the three useless. The stress in the two bolts (B) is thereby increased over what it would be if the middle bolt could act in unison with them. The compression set up between the flanges $\left(t'_b - \frac{T}{2}\right)$ further increases the stress in these end bolts. This compression is found to be largely

concentrated at the two points where contact between the two, abutting, end flanges begins (distant *e* from bolts B) and is due to the constraint which these end flanges reciprocally impose upon each other's freedom of flexure. (Cf. section A-A, Drawing Number 270). (This may be simply demonstrated in a practical manner by employing two strips of paste-board, to represent the end flanges loosely fastened together by three paper fasteners through punched holes and by exerting a " bifilar " pull in opposite directions at their ends.)

Assumptions of stress.

For simplification, the following assumptions are made:

(a) For Case I, the outer bolts (nearer the web) are neglected, since they are too near the center of rotation of the joint to be effective.

(b) Since the end bolts (B) of the inner three are much nearer the circumferential flanges than to the web of the segment, it is assumed that the bolt stresses are transmitted wholly to the circumferential flanges, in this case. A strip of the end flange parallel to its inner edge and of width l_1, twice the edge distance of the gage line of the inner bolts, is therefore treated as a beam, fixed ended in the circumferential flanges. Its axis is coincident with this bolt, gage line. The rest of the end flange towards the web is neglected as a factor contributing stiffness to this beam as no deduction is made, on the other hand, for bolt holes in the end flange.

(c) As noted earlier, the opening of a joint tends to reduce the area of compression (represented by l_n in Drawing Number 270) and consequently to increase the intensity of compressive stress at the extrados over what it otherwise would be. The neutral axis varies in position, with respect to the extrados from a minimum distance, l_n, at the face of the joint to a maximum, l_{n_1} somewhere in the body of the segment.

Development of Assumptions.

In order to evaluate this distance l_n, at the joint, which distance governs this reduction of area and consequently the intensification of pressure, it is necessary to approximate, at least, the distance from the face of the joint, back into the body of the segment where the neutral axis attains its normal position (Cf. Drawing No. 270). This trace of the segment's neutral surface is probably a curve; but it is assumed a straight line, or the distance in which the change takes place, $\frac{l_v\lambda}{2}$ is assumed to be shorter than it really is and, therefore, on the side of safety, as will be seen.

If there were induced no local compressive strains at the outer edge of the joint, the opening of the joint would concentrate the joint pressure upon its outer edge and an infinite compressive stress intensity would result. But it is reasonable to assume additional local strains which are accompanied by additional local stresses, as occurring. These additional strains are dissipated, as it were, through the distance $\frac{l_v\lambda}{2}$ into the segment, the region of compressive stress being delimited to the portion between the neutral axis and the extrados as described. In general,—

Let Δ_c = Total additional local strain of the extreme fiber at the joint (Drawing Number 270).

Then $\Delta_c = \frac{kl_v\lambda}{2E_c} z$, where z is a factor depending upon the shape of the curve assumed by the neutral axis, in the length of segment $\frac{l_v\lambda}{2}$ (Cf., also Nomenclature.)

But $l_n = \frac{\Delta_c}{\Theta}$ hence $l_n = z\, k\, l_v \frac{\lambda/2}{E_c\Theta}$

And to determine l_n in terms of k and Θ, it remains to evaluate $\frac{l_v\lambda}{2}$ and z.

If any thin vertical slice of the segment at the joint be taken (see Drawing Number 270) it will be seen that the moment of the compressive stresses is $C_j\ dl_n/3$, while that of the shears on the two sides of the slice is:

$$sl_n\ U\ d\ x.$$

Where s is the average intensity of shear in the face of the slice, and x is measured from the face of the joint; C_j for the purpose, is considered constant.

Equating the last two expressions, there is obtained

$$\frac{dl_n}{dx} = \frac{3sl_nU}{C_j}$$

Now the maximum shearing deformation in the slice is Θ. If the average shear, s, be based upon this maximum deformation, $\frac{dl_n}{dx}$ will be too large, i.e., the slope of the neutral axis will be too steep $\frac{l_v\lambda}{2}$ and therefore l, will be too small, which is on the side of safety. Making this assumption:

$$\frac{dl_n}{dx} = \frac{3G\Theta\ l_nU}{C_j}$$

As x increases Θ runs out to a value of zero in the body of the segment, hence the slope of the neutral axis curve $\frac{dl_n}{dx}$ evidently must decrease, as is evidenced in the last expression above. Taking this slope constant, $l_v\lambda$ is thereby made too small, and hence is again on the side of safety. This transition portion of the neutral axis, for $\frac{dl_n}{dx}$ = a constant, therefore, becomes a straight line, and

$$\frac{l_{n_1}-l_n}{l_v\lambda/2} = \frac{3G\Theta l_nU}{C_j}$$

$$\therefore \quad \frac{l_v\lambda}{2} = \frac{(l_{n_1}-l_n)C_j}{3G\Theta l_nU}$$

As $\frac{dl_n}{dx}$ is taken constant, z, in equation for $l_n = \frac{zkl_v\lambda/2}{E_c\ \Theta}$ becomes $1/2$ for an average as k is a maximum in the joint and becomes zero in the body of the segment, and there follows:

$$l_n = \frac{kl_v\lambda}{4E_c\Theta}$$

The approximate assumptions, therefore, included in the foregoing are three, as follows:

(1) Taking the compressive stress distribution at the extrados, at a joint, as triangular.

(2) Taking the average shear equal to the maximum shear.

(3) Taking the neutral axis from joint, into body of segment as a straight line.

But these assumptions, it is shown, are conservative.

Working Formulae.

The working formulae of Drawing Number 273 are derived accordingly for Cases A, B, and C, under Case I. Case B is really the limiting case, where e has increased from being smaller than $\frac{l_3}{2}$ (Case A) to being equal to $\frac{l_3}{2}$. The criterion is the expression:

$\left(l_2\sqrt{\frac{t'_b}{t'_b - T/_2}} - l_2\right)$ for all three cases and, for case C, gives a value greater than $\frac{l_3}{2}$ or beyond the greatest possible value that e can have. In Case C, there occurs a moment M_2 and a diminution of the compression, both at the single point of contact, at the middle bolt.

The expressions for Δ_1, M_1, M_2 and M_3, and e are derived in the ordinary manner taking account of the angular and linear deflections and forces involved, under the assumptions outlined.

CASE II

In connection with the following see Drawing Number 274, File Number 7 and Nomenclature for Case II.

JOINT AND BOLT ANALYSIS NOMENCLATURE

Compression in intrados

A	Area of cross-section of segment.
l'_{cg}	Distance from caulking groove to center of gravity of cross-section.
l_v	Length of segment.
U′	Twice the thickness of circumferential flange of ring at end of segment.
W	Thickness of web.
l'_b	Distance from caulking groove to C.L. of Outer Bolts.
l_4	Distance from root of end flange of segment to C.L. of Outer Bolts.
l_6	Effective width of cantilever beam formed by end flange.
l_p	Distance from caulking groove to line of pressure in the ring (P).
l'_p	Distance from caulking groove to resultant of line of pressure and effect of circumferential bolts.
l_{n_1}	Distance from caulking groove to neutral axis in body of segment.
l_n	Distance from caulking groove to highest point of contact of abutting segments.
λ	Ratio (Distance from face of joint to point where bending becomes normal) ÷ (Semi-length of segment).
e	Distance from C.L. outer bolts to point where contact of end flanges begins.
Δ_1	One-half maximum opening between abutting segments at C.L. outer bolts.
Θ	One-half angle between abutting segments.
I	Moment of inertia of cross-section of segment..
I'_1	Moment of inertia of cantilever beam formed by end flange of segment.
W'_1	Thickness of end flange at outer bolts.
A_B	Area of bolt.
l'_B	Semi-length of bolt.
P	Resultant thrust in the ring.
P′	Resultant of ring thrust and effect of circumferential bolts.
C_j	Total compression near inside of joint.
T	Total net tension transmitted from root of end flange to web of segment.
M	Bending moment in body of segment.
M_1	Bending moment at root of end flange.
M_2	Bending moment in end flange at C.L. of outer bolts.
t'_b	Total final stress in each outer bolt.
t_b	Total initial stress in each outer bolt.
E_c	Modulus of elasticity of cast iron in compression.
G	Modulus of elasticity of cast iron in shear.
k_1	Extreme compressive fiber stress in body of segment.
k	Extreme compressive fiber stress in joint, minus k_1.
k_{m_1}, k_{m_2}	Extreme ..... fiber stress due to M_1, M_2 respectively.
E_s	Modulus of elasticity of steel in tension.
A′	Cross-sectional area of segment disregarding all metal from intrados to bottom of caulking groove.
I′	Moment of inertia of segment, disregarding, etc., as for A′.
Δ_B	Semi-elongation of outer bolts.

Note: Corresponding to P′ and l'_p will be new values l'_{n_1} M′, k′ of l_{n_1}, M, k_1.

Longitudinal Joints or End Joints of Segment

The opening of the joint at the extrados, in this case causes modifications of the stresses in the bolt and segment, but somewhat different in character from those of Case I.

1. The area of compressive stress, now at the intrados, diminishes with a nearly proportional increase of intensity.

2. The flexure of the end flange induces bending moments in the flange and in the web immediately adjacent to its outer edge.

3. The flexure of the end flange somewhat increases the stresses in the bolts due to the pressure ($2t'_b$—T) set up between the flanges; but not by the full amount of this pressure. For, reference to the figure of Drawing Number 274, shows that the force ($2t'_b$—T) acts nearer to the center of rotation of the joint, in this case, than does the " pull " of the bolts.

Assumptions.

For simplification, the following assumptions are made:

(a) The inner bolts are neglected since they are too near the center of rotation of the joint to be of much effect, in Case II.

(b) The stresses of the outer bolts are assumed to be transmitted wholly to the web of the segment, as these bolts are much nearer the web than to the circumferential flanges. A strip of the end flange perpendicular to the web and having a width l_5 (Drawing Number 274) is regarded as a cantilever fixed at the web. The rigidity of the rest of the end flange towards the circumferential flanges is disregarded as no deduction was made for bolt holes, as before.

(c) The treatment of the quantity $l_v\lambda$, part of the expression for l_n, is identical with that described for Case I, with these exceptions:

The inner limit of compression area in the joint in Case II is at the bottom of the caulking groove and not the intrados.

The compression dissipates itself into the segment, moreover, downward to the intrados and upward to the neutral axis, therefore the dispersion is greater than for Case I, in a given distance in from the joint. That is, $\frac{l_v\lambda}{2}$ would be smaller for Case II if U, Θ, l_n and C_j were for some particular instance the same in Case I and Case II; thus, application of the formulae of Case I to Case II would lead to results on the side of danger.

Yet, a given compressive intensity at the intrados would be as dangerous, (because of the possibility of diagonal shearing failure at this point) as a much higher compressive stress confined to an area, the lower limit of which is the bottom of the caulking groove.

For the analysis of Case II joint stresses, therefore, the presence of all metal between the bottom of the caulking groove and the intrados, as noted on Drawing Number 274, is neglected, which is a more rigorous assumption than the actuality. With this assumption an expression for $l_v\lambda$ of a form identical with that of Case I may be used. The working formulae of Case II appear on Drawing Number 275, File Number 7.

Circumferential bolts.

In connection with the following, see Drawing Number 276, File Number 7.

Case I. Compression in extrados.

General considerations

The longitudinal joints of the tunnel (designated often as the end joints of a segment) are not continuous from ring to ring, but staggered, that is, each joint of a ring is spliced, as it were, by a segment or " plate " of each of the two adjacent rings. The effectiveness of this splice depends upon the completeness of the staggering, that is, a joint occurring at the middle of the length of the splicing segment is safer than if nearer its end. It also depends upon the friction set up, due to bolting operations, in the circumferential joints. The tighter the circumferential bolts are

bolted, the greater the amount of this friction and the better the " splice," if the term may be used in this respect.

To ascertain the amount by which the circumferential joint contributes to the relief of each of the several stresses tending to be developed in a longitudinal joint, the resultant R of all these frictional forces in the circumferential joints and induced by its bolts is determined.

Resultant R is then combined with thrust P (Figures 1, and 3, Drawing Number 276) on a longitudinal joint and the modified thrust P', distant l'_p from the extrados, that results includes the effect of the circumferential bolts' action.

The analysis of the longitudinal joint stress remains unchanged except that P' and l'_p are substituted for P and l_p, as shown on drawings numbered 270 and 274, File Number 7.

The determination of R is independent of the thrust in the ring and the longitudinal joints' local conditions, provided only that the opening 2Θ of the end joint, unsupported by the circumferential bolts, be great enough to cause incipient slipping in all parts of the circumferential joint, despite the stress produced by the reaction R upon the splicing segment.

If this obtains, the tension in the circumferential bolts and the coefficient of friction of cast iron on cast iron will determine the frictional forces completely. Any deformation of the splicing segment would modify slightly the directions of these frictional forces, only; but the uncertainty and probably small importance of this secondary effect it is believed did not warrant further consideration.

Detailed explanation.

Figure 1 of Drawing Number 276, File Number 7 shows that when the longitudinal joints of two adjacent rings open, under stress, there are a series of points along the extrados and intrados common to the two rings. Evidently, any pair of adjacent segment halves in the two rings will have points of relative rotation, common to the two and these points will lie somewhere in the line joining the intersection of their extradoses with that of their intradoses. The fixing of the center of relative rotation on this line remains to be accomplished.

Center of relative rotation.

Considering any two abutting segments in the same ring, it is seen that their center of instantaneous relative rotation lies near the extrados somewhere in the area covered by l_n (Drawing Number 270). Where l_n is small, this center can be taken without serious error at the extrados. So taking it, it follows that points on the extrados of two abutting segments are the only two points which are stationary with respect to each other. Hence points of relative rotation of adjacent segment halves in different rings lie at the extrados. Since they lie also in the line joining intersections of extradoses and intradoses, they must lie at the intersection points of extradoses, as noted, on Drawing Number 276.

Directions of frictional forces.

The directions taken by frictional forces are perpendicular to radial lines proceeding from the corresponding centers of rotation. These forces have been assumed as concentrated at the centers of the bolts which occasion them. The expressions for the magnitude and position of 2R, shown on Drawing Number 276, then follow.

Effect on longitudinal joint.

2R does not represent the force acting upon a longitudinal joint, however; but this force is R, one-half of the entire resultant of frictional forces.

If attention be concentrated upon one ring, for the time being, it can be stated that the combination of 2R, the resultant, with the resultant thrust at the center of the segment considered gives the resultant thrust at the joint.

This resultant thrust at the center of segment is not yet known, for it too is affected by the action of the circumferential bolts.

Next, consideration of two adjacent rings (wherein a section through the center of a segment in one ring and a joint in the other, is taken) leads to the following:

For the center of segment, Resultant Thrust $= P'_2$

For the adjacent joint, Resultant Thrust $= P' = P'_2 + 2R$

Adding, the total resultant for two rings $= 2P'_2 + 2R$

But the total for two rings $= 2P$

$$P = P'_2 + R$$

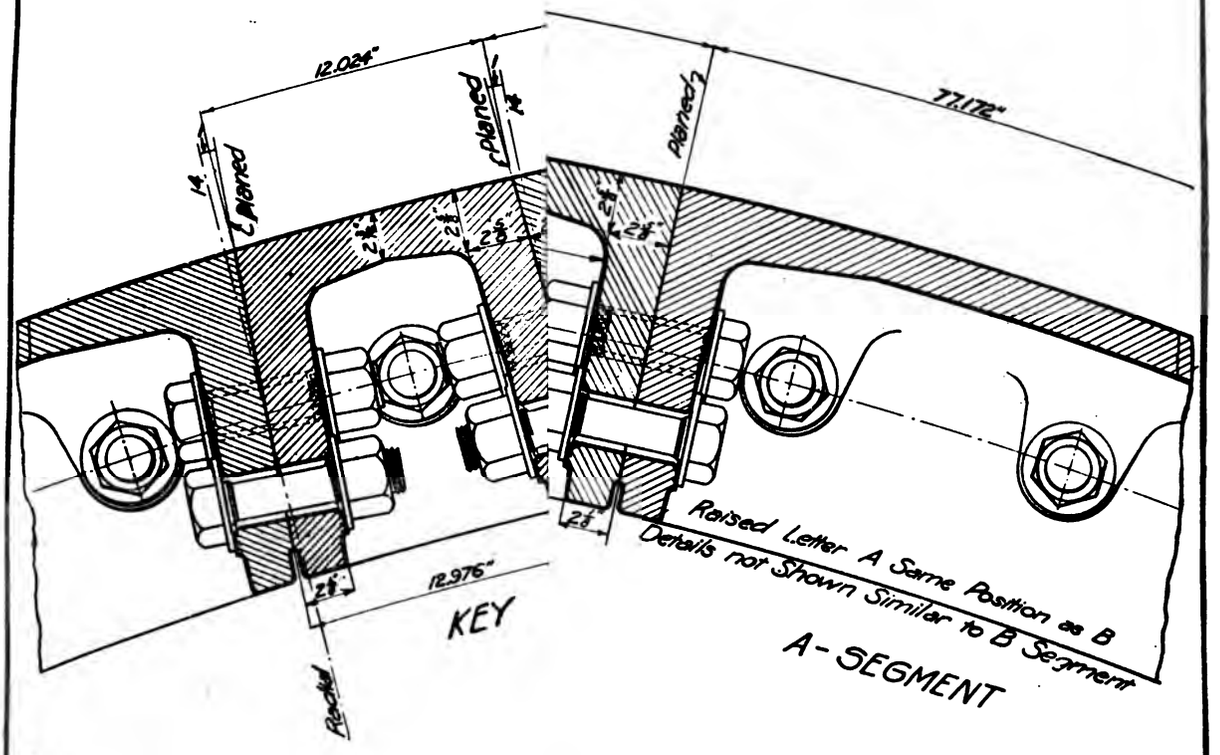
Whence $P'_2 = P - R$ and $P' = P + R$, as given on Drawing Number 276, File 7.

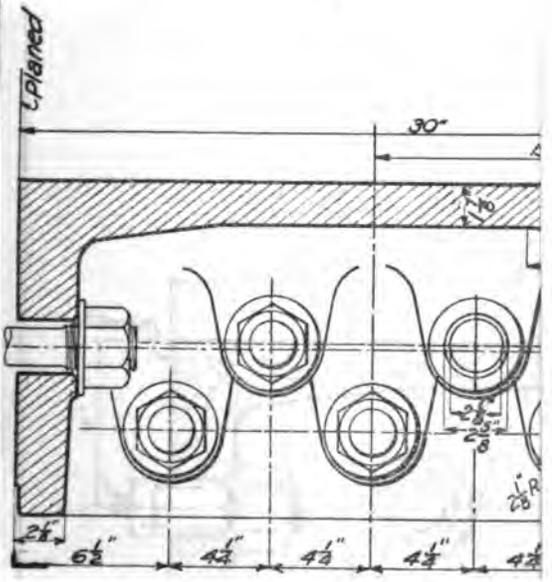
Thus the formulae of this drawing, just cited, offer the complete solution for the effect of these circumferential bolts upon the stresses in the longitudinal joints and the body of the segment.

In applying the working formulae of Drawing Number 276, two positions of the center of relative rotation are used. When l_n is small, or the failure of the end joint of a segment, without assistance from the circumferential joints, is imminent, the center is taken at the extrados.

When l_n is comparatively large or the joint is comparatively secure, the center is taken in the gage line of the circumferential bolts, which last position minimizes the effect of these bolts.

Case II. This is covered by the note at the bottom of Drawing Number 276, File Number 7.





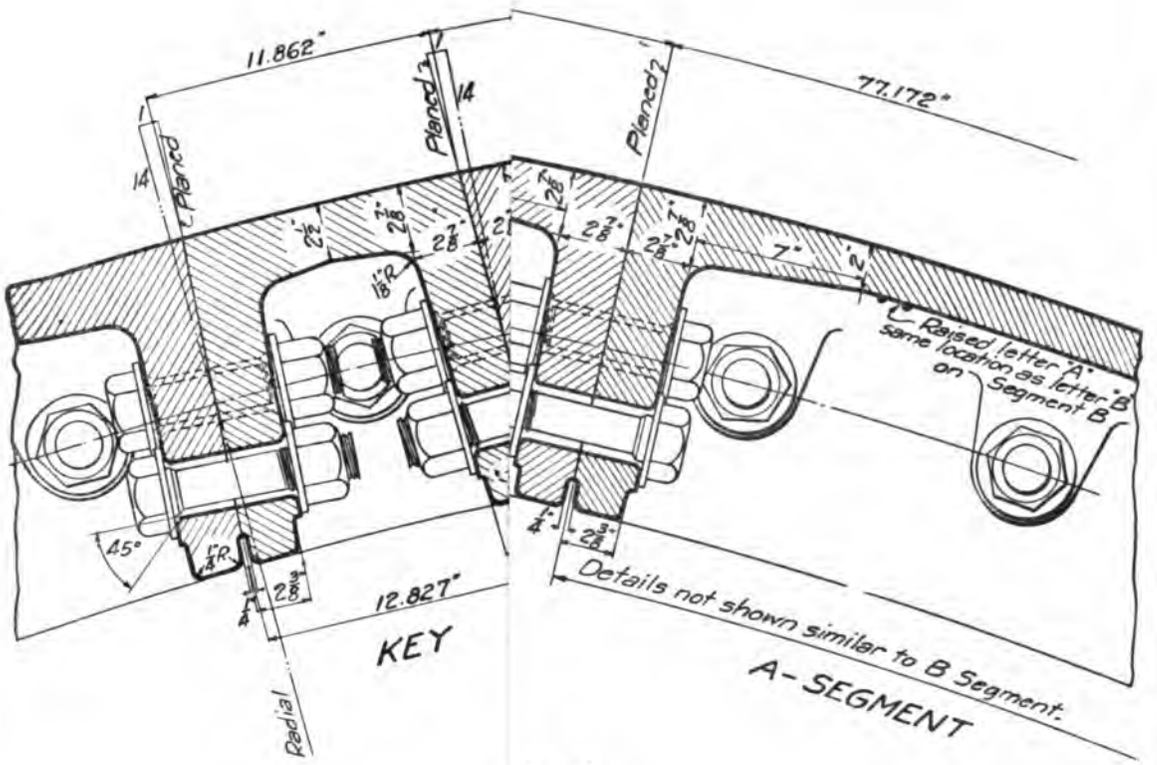
SECTION A-A

NEW YORK STATE
BRIDGE & TUNNEL COMMISSION
AND
NEW JERSEY INTERSTATE
BRIDGE & TUNNEL COMMISSION

HUDSON RIVER VEHICULAR TUNNEL
29FT. DIAMETER TUNNEL
CAST IRON DETAILS
ORDINARY SECTION

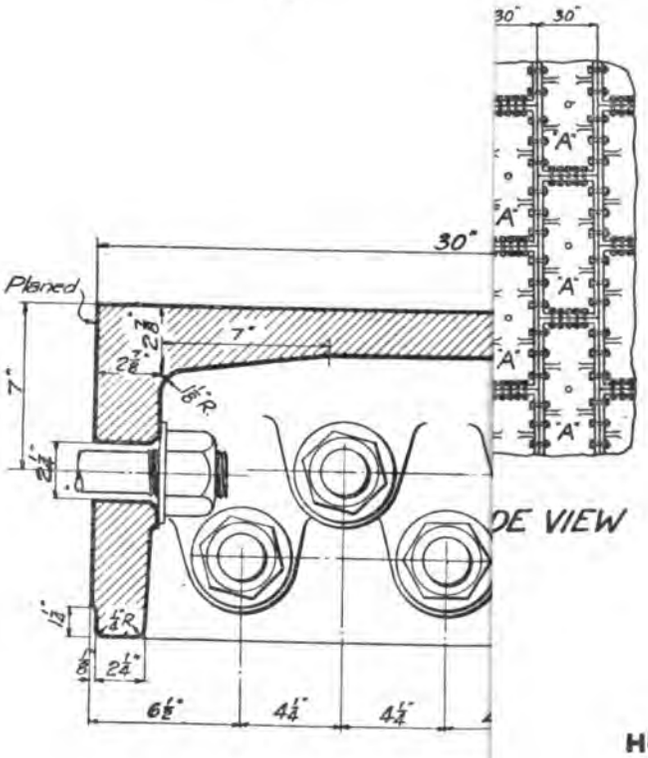
SCALE: 0 1 2 3 4

FILE Nº 7
DRAWING Nº 134



KEY

A-SEGMENT



SECTION

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BRIDGE & TUNNEL COMMISSION

HUDSON RIVER VEHICULAR TUNNEL

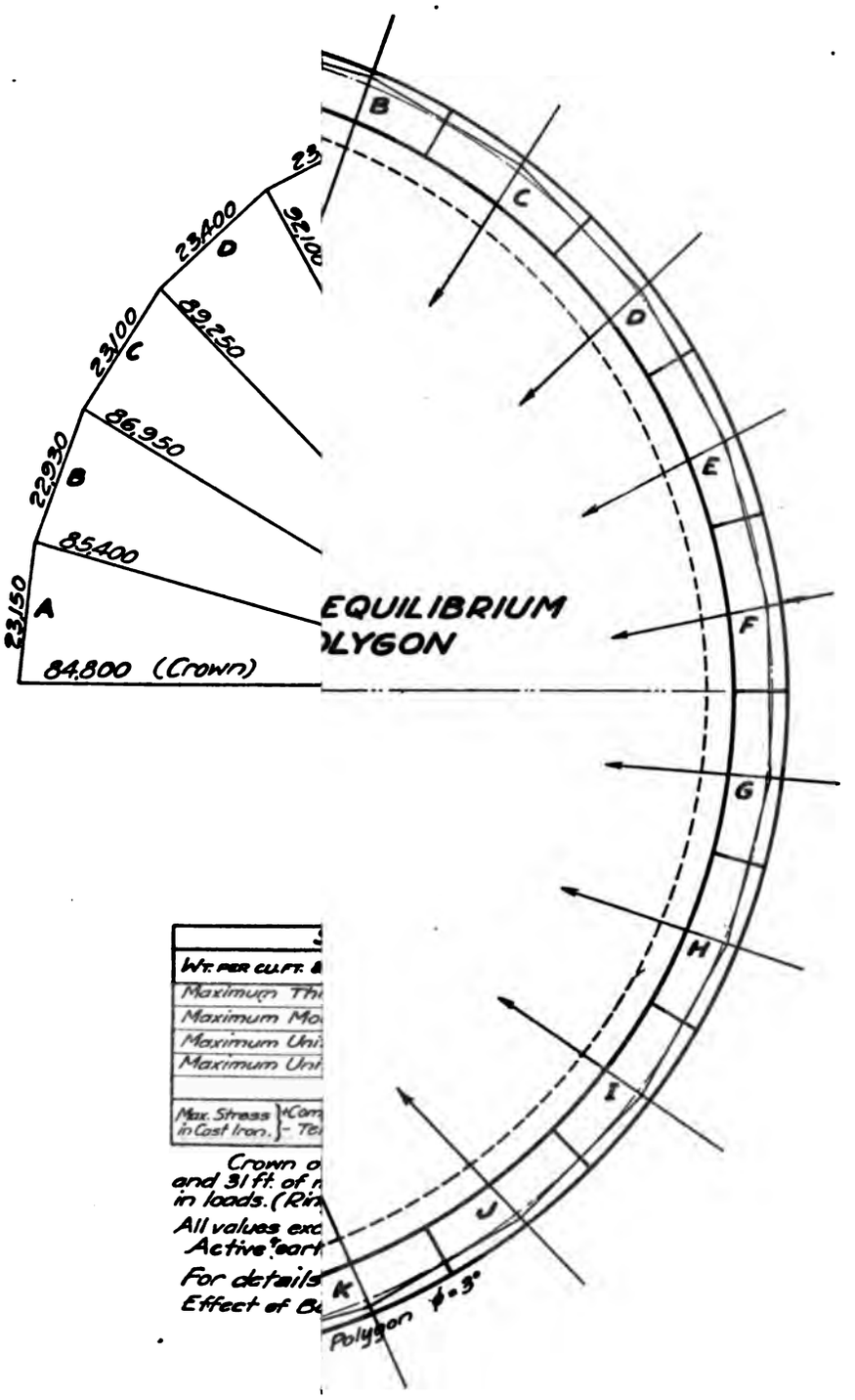
29 FT. DIAMETER TUNNEL

CAST IRON DETAILS

HEAVY SECTION

SCALE: 0 1 2 3 4

FILE Nº 7
DRAWING. Nº 135



Wt. per cu.ft. &	
Maximum Thi	
Maximum Mo	
Maximum Uni	
Maximum Uni	
Max. Stress in Cast Iron.	+Com - Te

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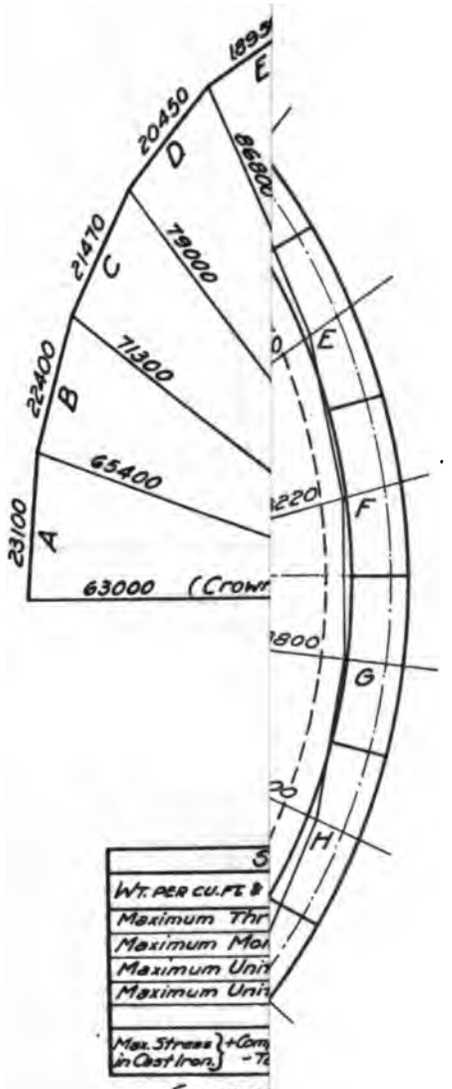
BRIDGE & TUNNEL COMMISSION

HUDSON RIVER VEHICULAR TUNNEL
29 FT. CAST IRON RING
ARCH ANALYSIS
ϕ = 3°

SCALE: 1/2" = 1'
1" = 15000 POUNDS

DRAWN BY M.J.O. 4/14/30
CHECKED BY J.M.
FILE NO. 7

DRAWING NO. 164



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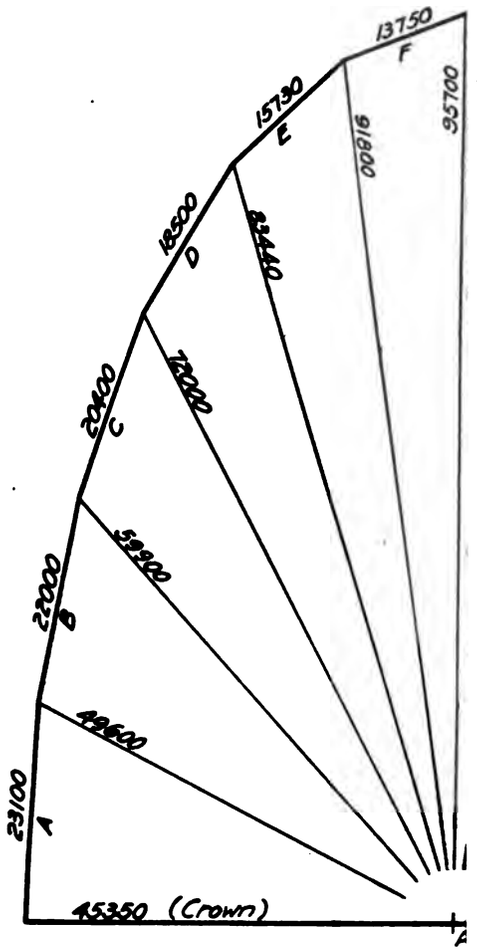
HUDSON RIVER VEHICULAR TUNNEL
29 FT. DIAM. CAST IRON RING
ARCH ANALYSIS
ϕ 11°-18'

SCALE: 1" = 1'-0"
1" = 15000 POUNDS

DRAWN BY R.S.B.
CHECKED BY W.R.G. Jr.
FILE NO. 7

DRAWING NO. 171



FORCE
(Crown Thr

SUMMARY OF
Wt. PER CU.FT. & ANGLE OF REPOS
Maximum Thrust Normal To
Maximum Moment
Maximum Unit Compression in
Maximum Unit Tension in Cas
Max. Stress in Cast Iron } + Compression (Extrados
} − Tension (Intrados

Crown of Tunnel is as
and 31 ft. of mud. Weight o
in loads. (Ring alone would
All values except unit stres
Active "earth" pressures
for details of C.I. Segn
Effect of Bolts & Joints n

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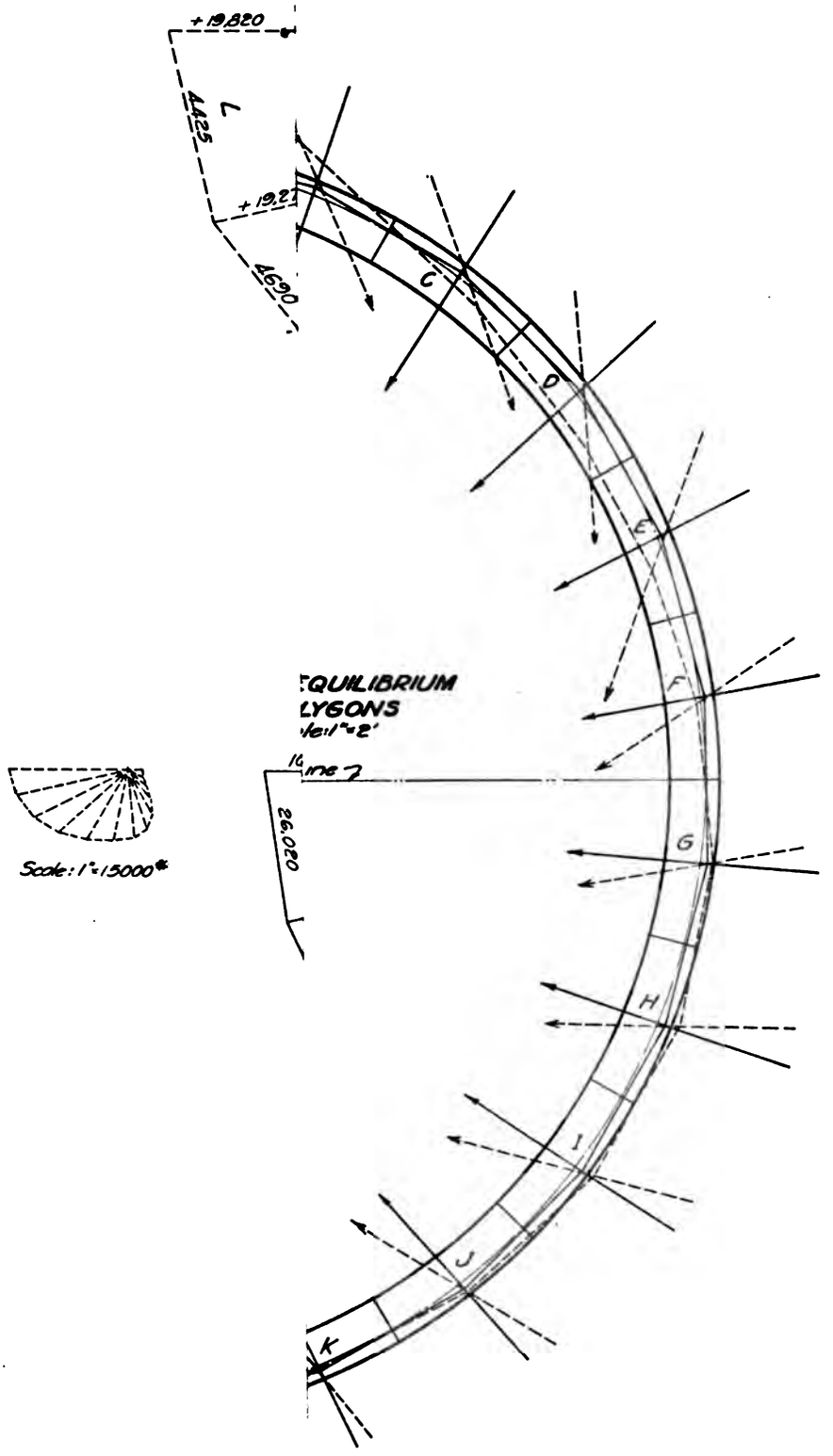
BRIDGE & TUNNEL COMMISSION

HUDSON RIVER VEHICULAR TUNNEL
29FT. DIAM. CAST IRON RING
ARCH ANALYSIS
$\phi = 20°$

SCALE: 1"=1'-0"
1" = 10000 POUNDS

DRAWN BY H.O.A. Jr.
CHECKED BY M.C.
FILE NO. 7

DRAWING NO. 172



Summary of
Maximum Thrust normal to joint
Maximum Moments.
Maximum Unit Compression in Cast Iron.
Maximum Unit Tension in Cast Iron.
Stress f_c Cast Iron. } + Compression { Extrados Crown +20
- Tension { Intrados +1

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HUDSON RIVER VEHICULAR TUNNEL

ANALYSIS - 29 FT. CAST IRON RING

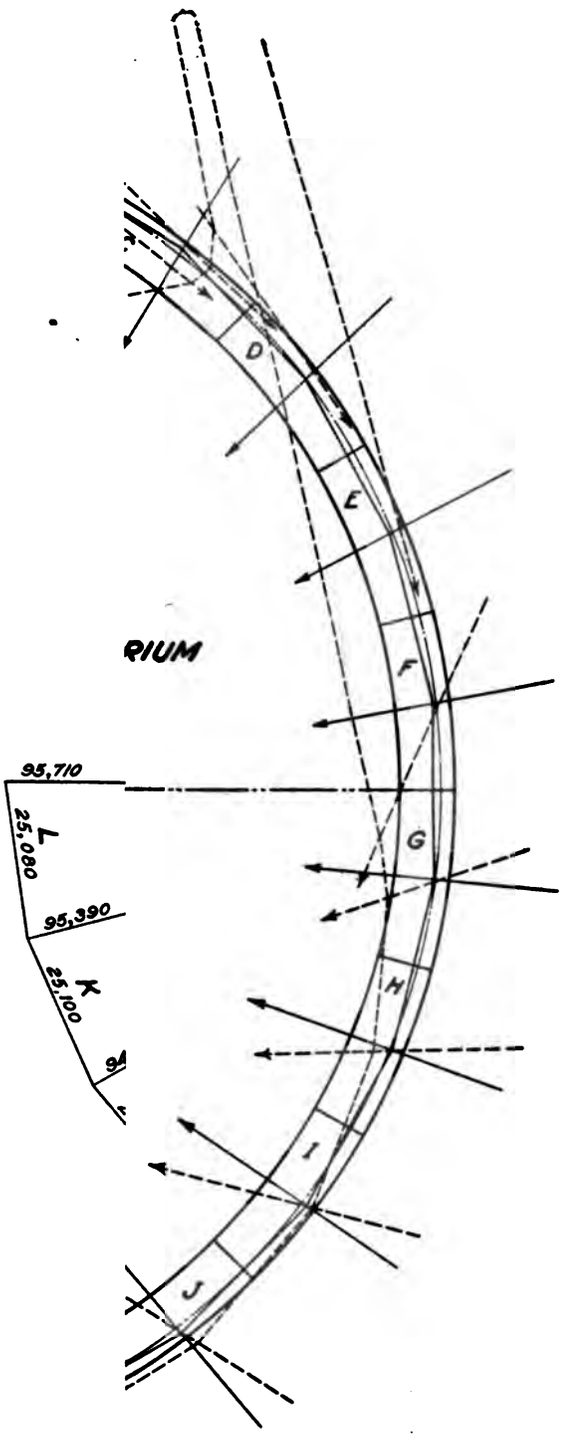
RING ALONE AND WITH COMPRESSED AIR

$\phi = 3°$

SCALES: AS SHOWN

DRAWN BY M.C.
CHECKED BY J.M.
FILE NO. 7

DRAWING NO. 175



Scale: 1" = 15,000#

Summary of Results of		Ring at
		Location
Maximum Thrust normal to joint.		Invert
Maximum Moments.		Crown
Maximum Unit Compression in Cast Iron.		Joint E-F
Maximum Unit Tension in Cast Iron.		Crown
Stress in Cast Iron.	+ Compression	Crown (Extrados) f.R. 2.65
		Haunch (Extrados) +12.80
	- Tension	Crown (Intrados) - 4.50
		Haunch (Intrados) +3.685

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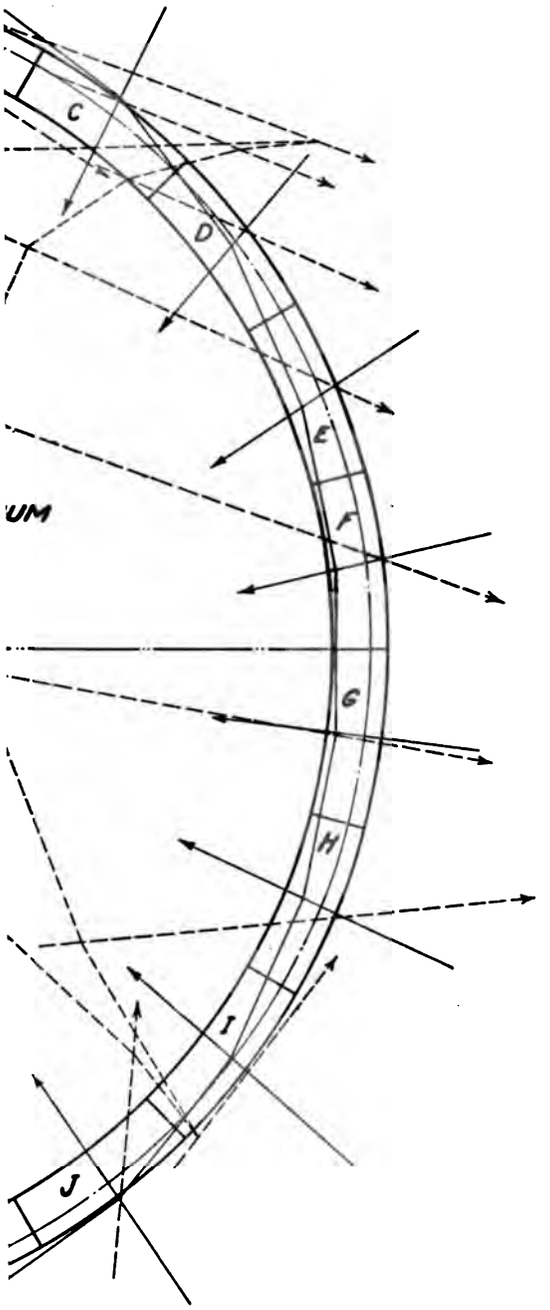
HUDSON RIVER VEHICULAR TUNNEL
ANALYSIS - 29 FT. CAST IRON RING
RING ALONE AND WITH COMPRESSED AIR
$\phi = 5°$

LES: AS SHOWN.

WN BY M.C.
CKED BY J.M
E NO. 7

DRAWING NO. 176



Scale: 1"=15,000#

SUMMARY	
Maximun Thrust normal to joint	
Maximun Moments.	
Maximun Unit Compression in Cast	
Maximun Unit Tension in Cast Iro	
Stress in Cast Iron	+ Compression (Crown Extrados -1,55; Intrados :=8,7)
	- Tension

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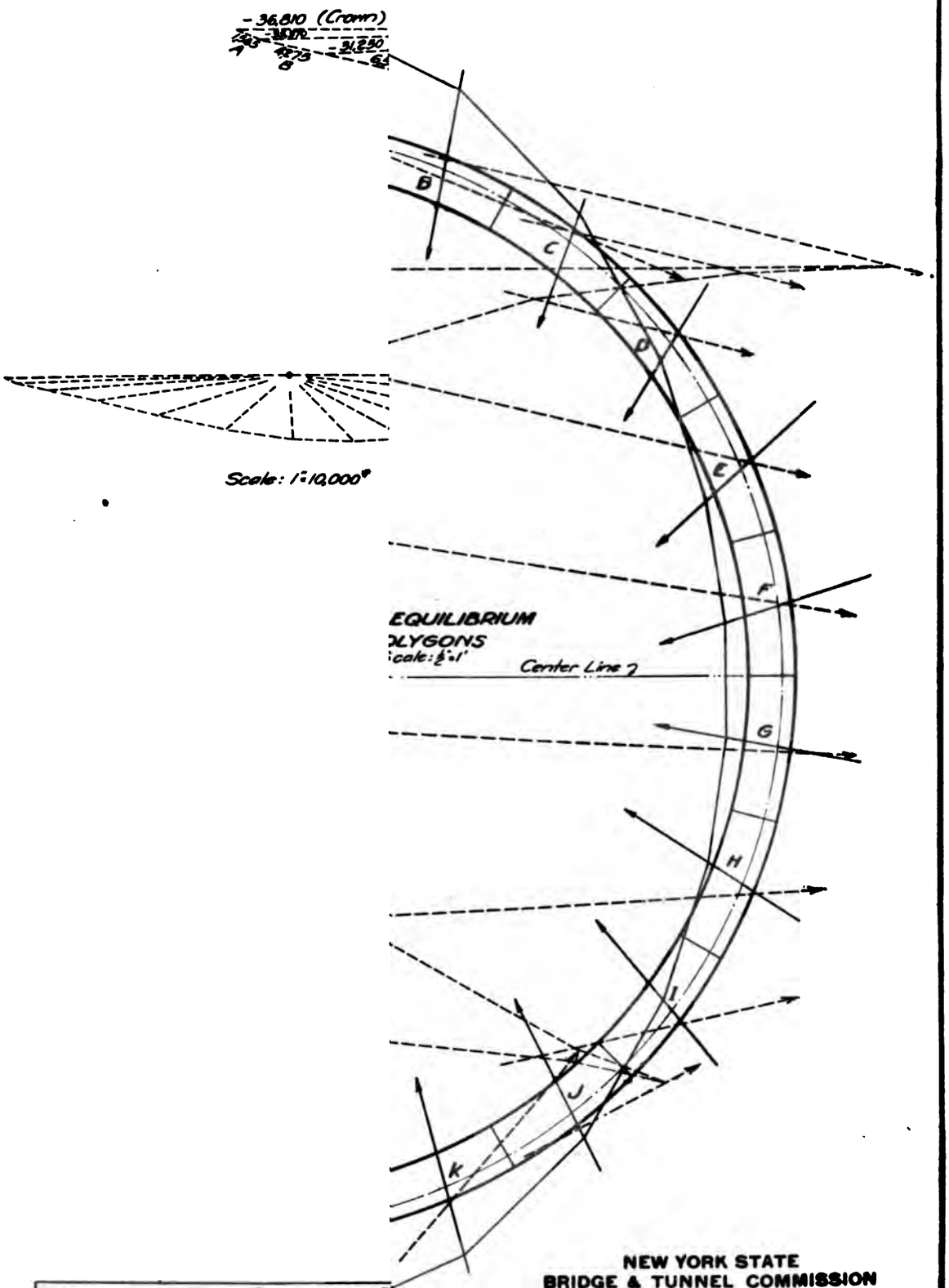
HUDSON RIVER VEHICULAR TUNNEL
ANALYSIS -29 FT. CAST IRON RING
RING ALONE AND WITH COMPRESSED AIR
$\phi = 11°-18'$

SCALES: AS SHOWN

DRAWN BY M.C.
CHECKED BY J.M.
FILE NO. 7

DRAWING NO. 178



Summary of R	
Maximum Thrust normal to joint	
Maximum Moments	
Maximum Unit Compression in Cast Iron.	
Maximum Unit Tension in Cast Iron	
Stress in Cast Iron	+Compression, Crown, Extrados +5,820
	-Tension, Intrados -17,880

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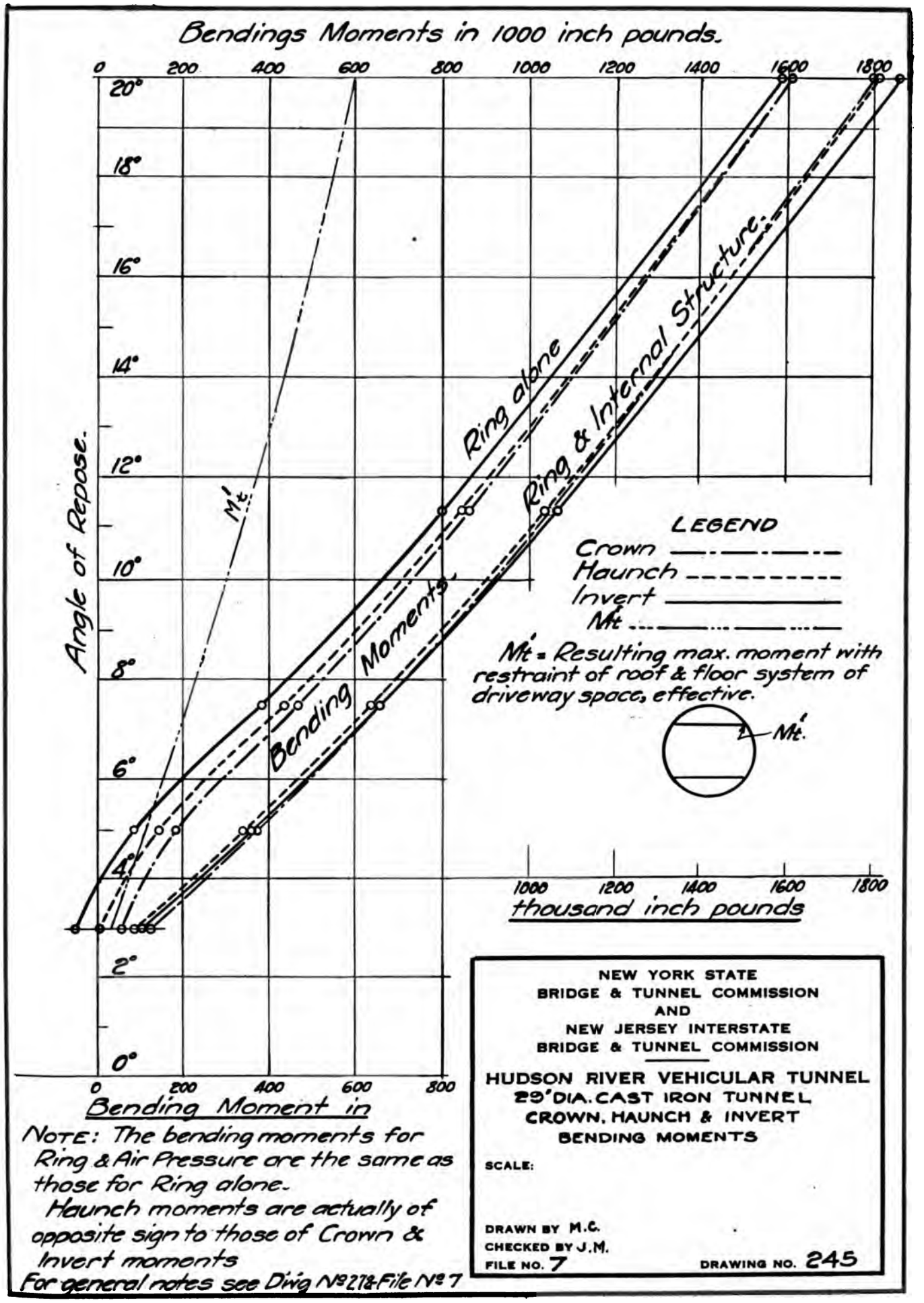
HUDSON RIVER VEHICULAR TUNNEL

ANALYSIS-29 FT. CAST IRON RING
RING ALONE AND WITH COMPRESSED AIR
$\phi = 20°$

SCALES AS SHOWN

DRAWN BY M.C.
CHECKED BY JM
FILE NO. 7

DRAWING NO. 179



NOTE: The bending moments for Ring & Air Pressure are the same as those for Ring alone.
Haunch moments are actually of opposite sign to those of Crown & Invert moments
For general notes see Dwg No 218 & File No 7

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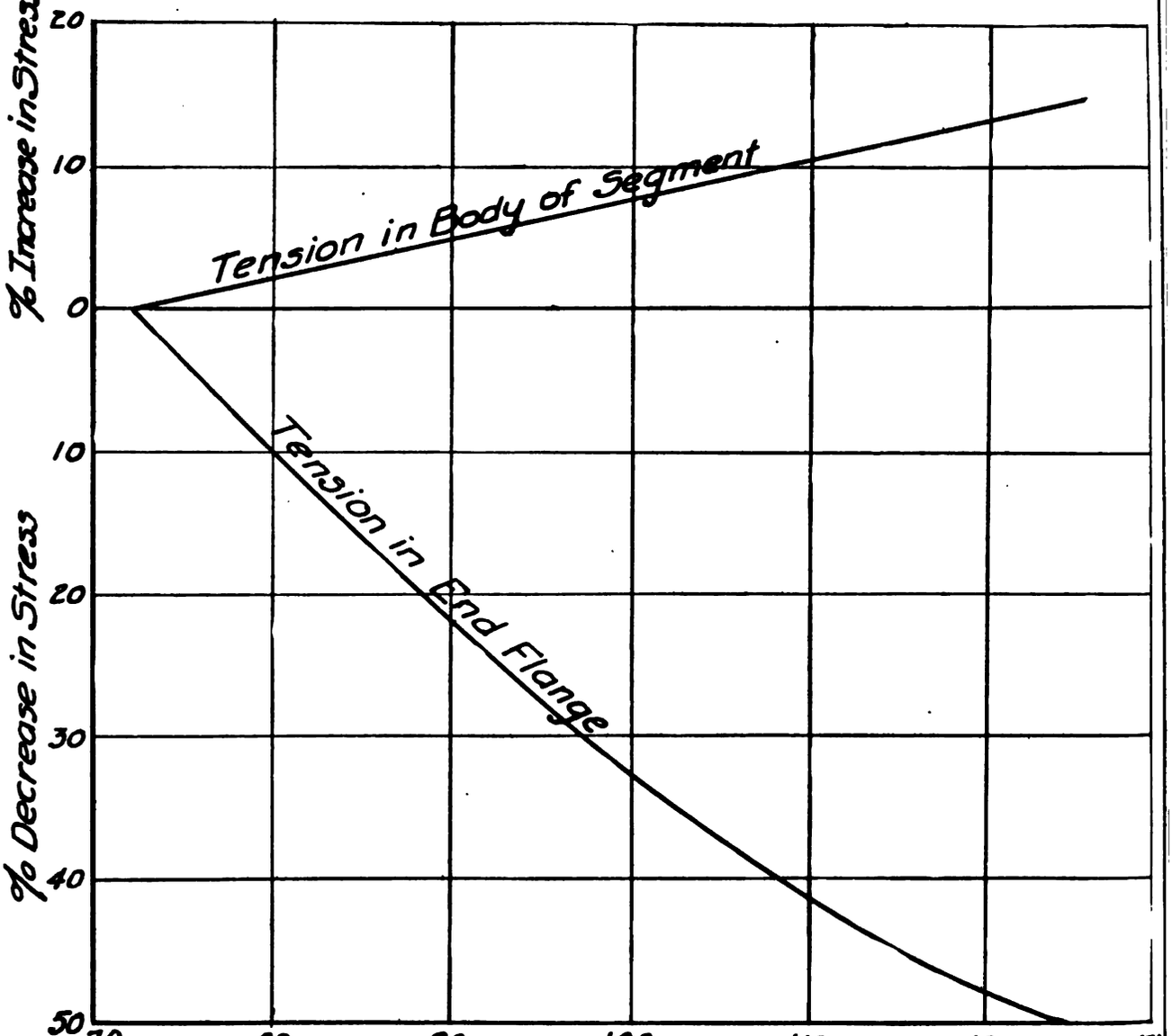
HUDSON RIVER VEHICULAR TUNNEL
29'DIA. CAST IRON TUNNEL
CROWN, HAUNCH & INVERT
BENDING MOMENTS

SCALE:

DRAWN BY M.C.
CHECKED BY J.M.
FILE NO. 7
DRAWING NO. 245



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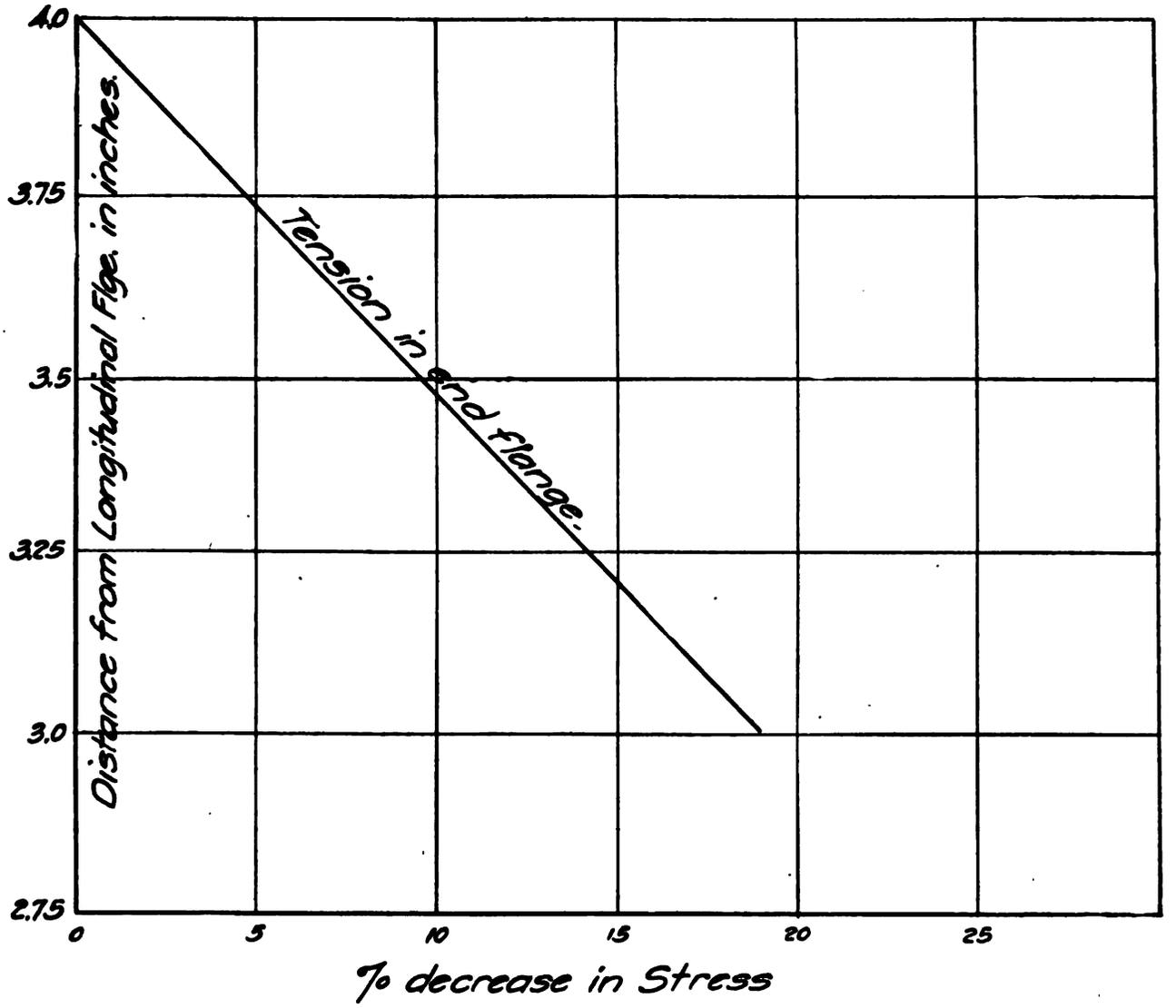
HUDSON RIVER VEHICULAR TUNNEL
29' DIA. C.I. TUNNEL - HEAVY SECT.
PERCENT STRESS VARIATIONS
WITH CHANGE IN TOTAL BOLT TENSION

SCALE: DATE JAN. 22 - 1921

DRAWN BY H.S.B.
CHECKED BY M.C.
FILE NO. 7 DRAWING NO. 262



Bolts assumed stressed initially to elastic limit (40,000#/□").

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HUDSON RIVER VEHICULAR TUNNEL
29'DIA. C.I. TUNNEL
PER CENT STRESS VARIATION
WITH CHANGE IN BOLT POSITION

SCALE: DATE JAN. 22, 1921

DRAWN BY M.C.
CHECKED BY H.S.B.
FILE NO. 7 DRAWING NO. 261

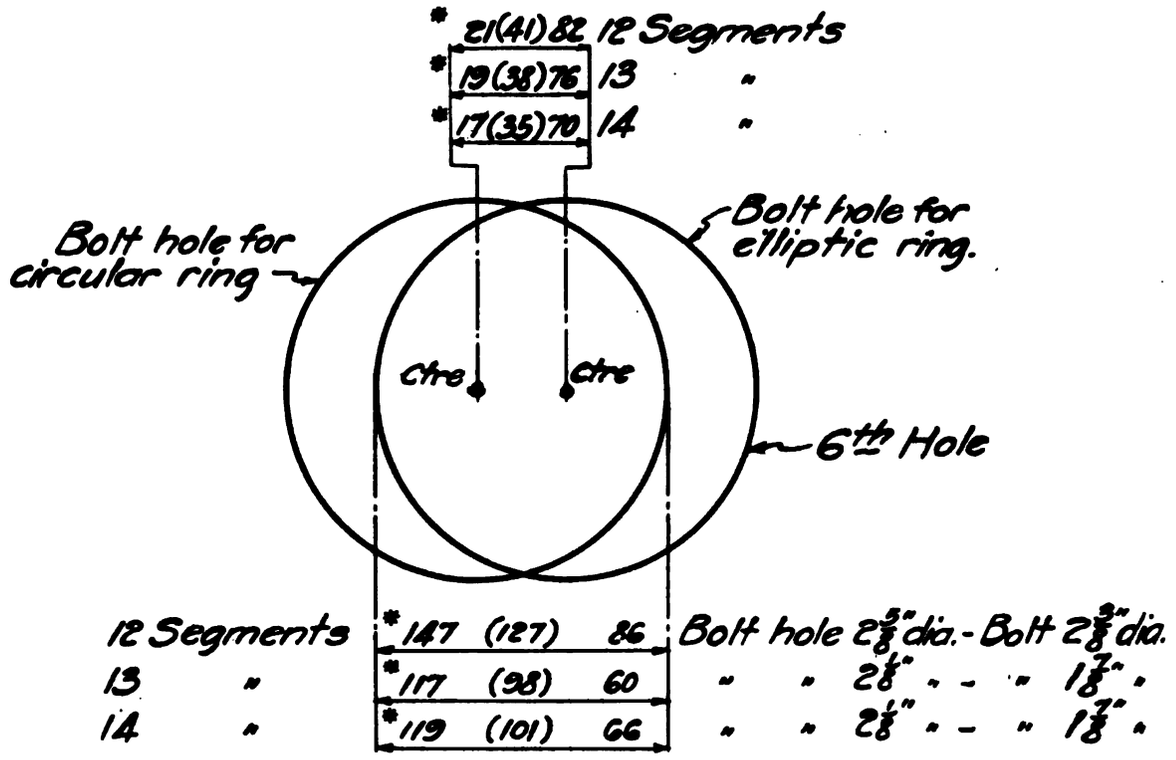
Clearances given in 64ths of an inch.
* 21(41)82 12 Segments
* 19(38)76 13 "
* 17(35)70 14 "
Bolt hole for circular ring
Bolt hole for elliptic ring.
ctre
ctre
6th Hole
12 Segments * 147 (127) 86 Bolt hole 2 5/8" dia. - Bolt 2 3/8" dia.
13 " * 117 (98) 60 " " 2 5/8" " " 1 7/8" "
14 " * 119 (101) 66 " " 2 5/8" " " 1 7/8" "

FIGURE 1.

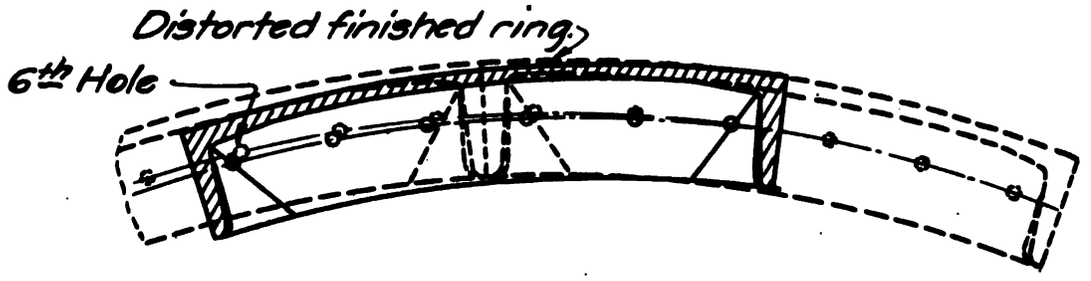

FIGURE 2.

NOTE:

Figures shown by an asterisk are for a decrease of 1½" of the vertical dia., and an increase of 1½" of the horizontal dia. from the circular.

Figures in ( ) are for a decrease of 3" of the vertical dia., and an increase of 3" of the horizontal dia., from the circular.

Other figures are for a decrease of 6" of the vertical dia. and an increase of 6" of the horizontal dia. from the circular.

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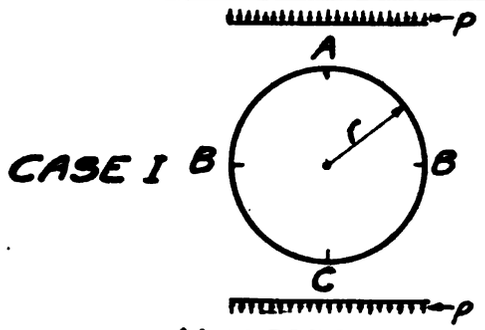
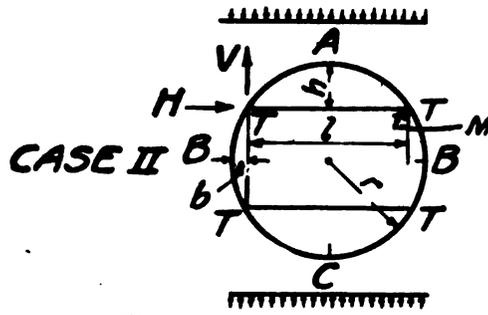
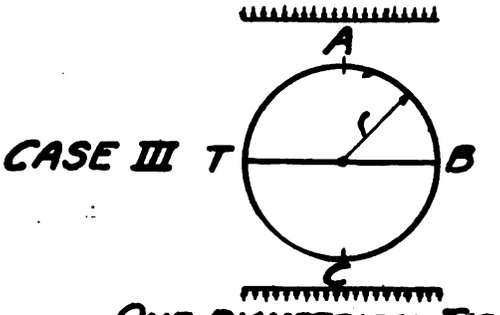
HUDSON RIVER VEHICULAR TUNNEL
29' DIA. C.I. TUNNEL - HEAVY SECTION
DRIFT-PIN CLEARANCES

SCALE:

DRAWN BY J.H.O
CHECKED BY O.F.B.
FILE NO. 7

DRAWING NO. 264

*(1) Structure considered elastic; but its weight neglected.
(2) Moments at A, B and C and at ends of Ties, Ma, Mb, Mc and Mt with Mt'.
(3) Vertical Intensity = p. Radius = r.
(4) Horizontal Reaction = H; Vertical = V; at left end of Tie.
(5) For 29' tunnel: r = 14.5 h = 7.25 l = 25.11 b = r - h/2. (Cf. Fig.)
whence: h = 0.5r; l = 1.732r; b = 0.134r; V = 0.866pr.
(6) $Ma = Mt - Hh + \frac{1}{2}Vl - \frac{1}{8}pl^2$ and $Mb = Mt - Vb - \frac{1}{2}pb^2$ (for Case II.)

	BENDING MOMENTS (Effect of Axial Stress neglected.)	
 CASE I UNRESTRAINED	$Ma = -Mb = Mc = 0.25pr^2$	
 CASE II RESTRAINED BY TIES T-T	HINGED AT TIE END	FIXED AT TIE END
	$M_a = M_c = +0.018pr^2$ $Mt = 0$ $Mb = -0.125pr^2$ $(H = 0.714pr)$	$(H = 0.784pr)$ $Ma = Mc = +0.011pr^2$ $Mt = +0.028pr^2$ $Mt' = +0.0818pr^2$ $Mb = -0.043pr^2$ * For Arc between Ties.
 CASE III ONE DIAMETRICAL TIE	$Ma = Mc = +0.076pr^2$ $Mt = Mb = 0$ $(H = 0.424pr)$	$Ma = Mc = +0.046pr^2$ $Mt = Mb = +0.106pr^2$ $(H = 0.560pr)$

For tension in tie rod use:
In Case II, force = H
In Case III, force = 2H

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HUDSON RIVER VEHICULAR TUNNEL
29' DIA. C.I. TUNNEL
RING RESTRAINED BY HORIZONTAL TIES

SCALE: DATE JAN. 22, 1921

DRAWN BY O.A.B.
CHECKED BY N.S.C.
FILE NO. 7 DRAWING NO. 267

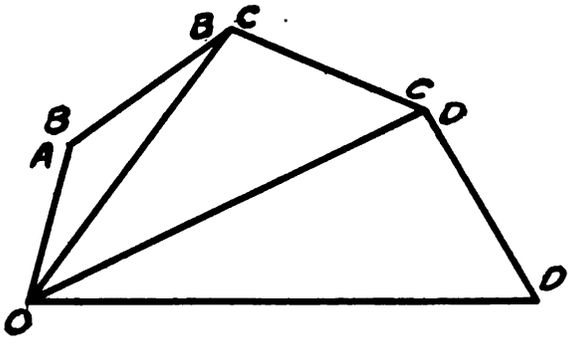

FIGURE 1.

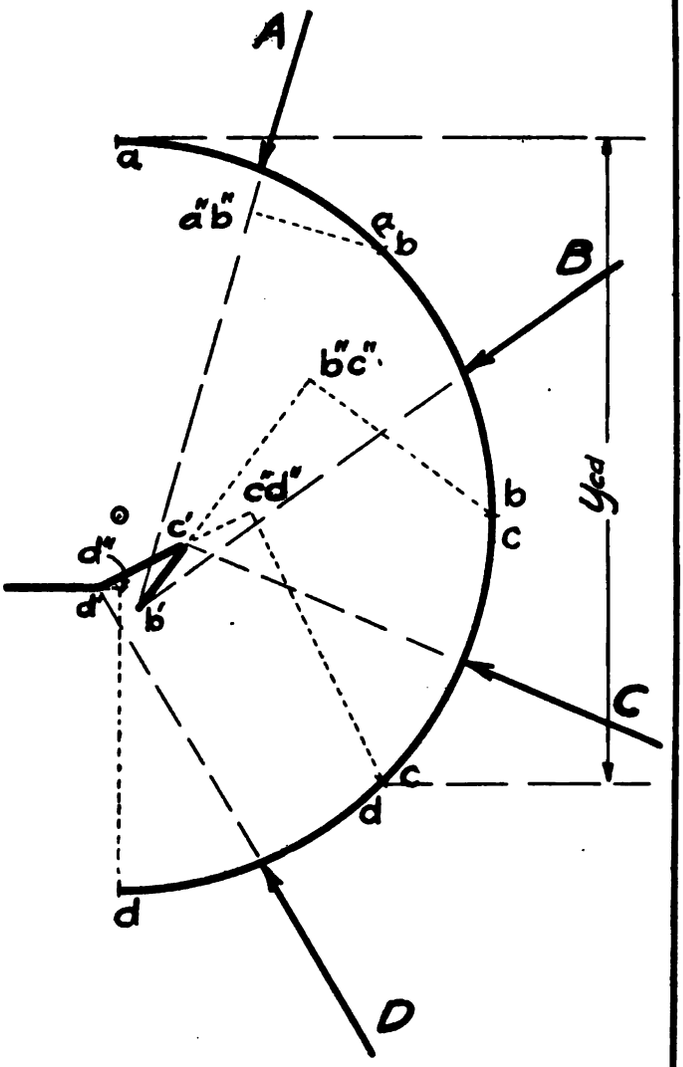

FIGURE 1A.

Funicular polygon for zero crown thrust & zero crown moment is b'c'd'.

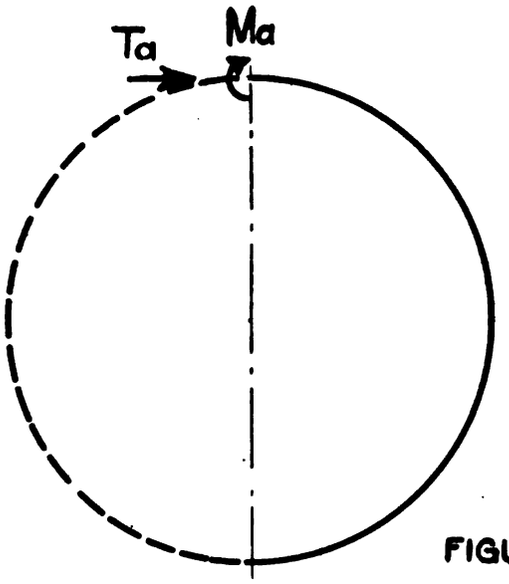

FIGURE 2.

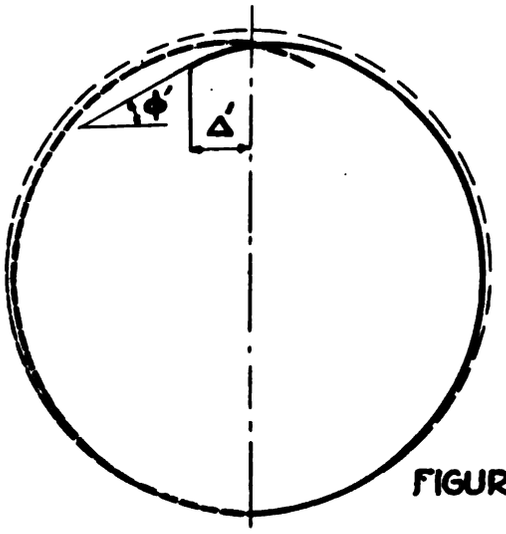

FIGURE 3.

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HUDSON RIVER VEHICULAR TUNNEL

ANALYSIS BY DEFLECTION METHOD

SCALE:

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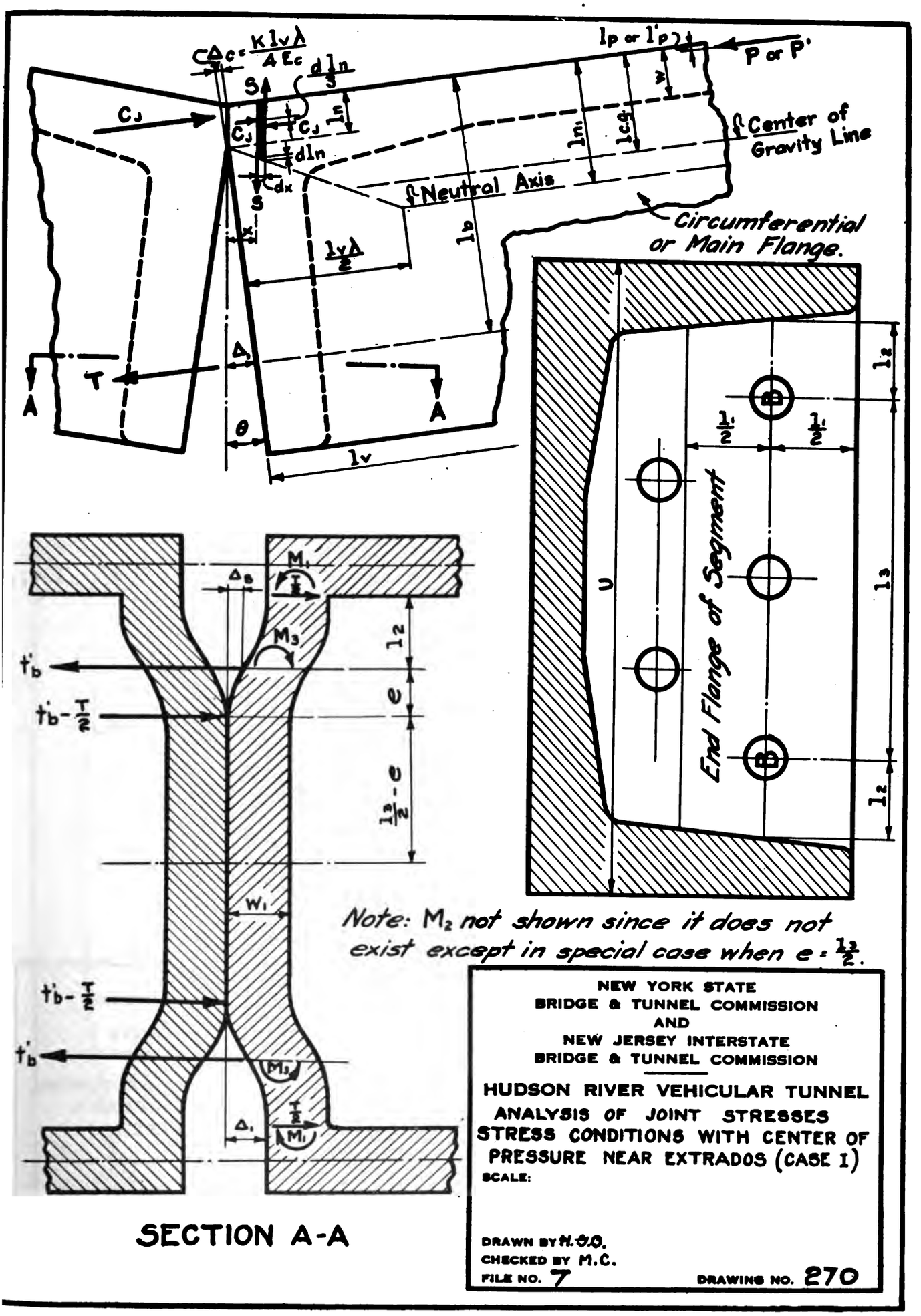
CHECKED BY O.L.B.
FILE NO. 7
DRAWING NO. 269


Center of Gravity Line
Neutral Axis
Circumferential or Main Flange.
End Flange of Segment
P or P'
SECTION A-A
Note: M2 not shown since it does not exist except in special case when e = l3/2.

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HUDSON RIVER VEHICULAR TUNNEL
ANALYSIS OF JOINT STRESSES
STRESS CONDITIONS WITH CENTER OF PRESSURE NEAR EXTRADOS (CASE I)

SCALE:

DRAWN BY H.O.O.
CHECKED BY M.C.
FILE NO. 7
DRAWING NO. 270

Case A $l_2\left(\sqrt{\frac{t_b'}{t_b'-\frac{1}{2}T}}-1\right)<\frac{l_3}{2}$

$e=l_2\left(\sqrt{\frac{t_b'}{t_b'-\frac{1}{2}T}}-1\right)$ $\qquad M_1=-\frac{T}{2}(l_2+e)+e\,t_b'$

$M_2=0$ $\qquad M_3=e\left(t_b'-\frac{1}{2}T\right)$

$\Delta_1=\frac{l_2^3\,t_b'}{6E_cI_1}\left[\sqrt{\frac{t_b'}{t_b'-\frac{1}{2}T}}-1\right]$ $\qquad \Delta_B=\frac{e^3}{6E_cI_1}\left[t_b'-\frac{1}{2}T\right]$

Case B $l_2\left(\sqrt{\frac{t_b'}{t_b'-\frac{1}{2}T}}-1\right)=\frac{l_3}{2}$

$e=\frac{l_3}{2}$ $\qquad M_1=-\frac{T}{2}(l_2+e)+e\,t_b'$

$M_2=0$ $\qquad M_3=e\left(t_b'-\frac{1}{2}T\right)$

$\Delta_1=\frac{t_b'}{6E_cI_1}\left[\frac{l_3\,l_2^2}{2}\right]$

Case C $l_2\left(\sqrt{\frac{t_b'}{t_b'-\frac{1}{2}T}}-1\right)>\frac{l_3}{2}$

$e=\frac{l_3}{2}$ $\qquad M_1=-\frac{T}{2}(l_2+e)+et_b'+M_2=\frac{t_b'e^2}{2(l_2+e)}-\frac{T}{4}(l_2+e$

$M_2=\frac{t_b'\,l_2^2}{2\left(l_2+\frac{l_3}{2}\right)}-\frac{\left(t_b'-\frac{1}{2}T\right)\left(l_2+\frac{l_3}{2}\right)}{2}$ $\qquad M_3=e\left(t_b'-\frac{1}{2}T\right)+M_2=\frac{t_b'l_2^2}{2(e+l_2)}+\frac{1}{2}\left(t_b'-\frac{1}{2}T\right)(e-l_2)$

$\Delta_1=\frac{1}{E_cI_1}\left[\frac{T}{2}\left(\frac{1}{12}l_2^3+\frac{1}{8}l_2^2\,l_3+\frac{1}{16}l_2\,l_3^2+\frac{1}{96}l_3^3\right)-t_b'\left(\frac{1}{16}l_2\,l_3^2+\frac{1}{96}l_3^3\right)\right]$

$\Delta_B=\frac{1}{6E_cI_1}\left[e^3\left(t_b'-\frac{1}{2}T\right)+3M_2e^2\right]$

Cases A.B.C.

$l_n=\frac{Ik_1}{M}$, $k_1=\frac{P}{A}+\frac{M\,l_{c.g.}}{I}$, $M=P(l_{c.g.}-l_p)$

l_n = assumed

$T=\frac{P\left(\frac{l_n}{2}-l_p\right)}{l_b-\frac{l_n}{3}}$

Δ_1 = (see above)

$\theta=\frac{\Delta_1}{l_b-l_n}=\frac{k\,l_v\,\lambda}{4E_cI_n}$ whence $l_n=\frac{k\,l_v\,\lambda}{4E_c\theta}$

$C_j=P+T$

$\lambda=\frac{2(l_{n_1}-l_n)C_j}{3\,l_vG\theta\,l_n\,U}$

$k=\frac{2C_j}{U\,l_n}-k_1$

$l_n=\frac{k\,l_v\,\lambda\,l_b}{4E_c\Delta_1+k\,l_v\,\lambda}$

$t_b'-t_b=\frac{\Delta_B\,E_s\,A_s}{l_B}$

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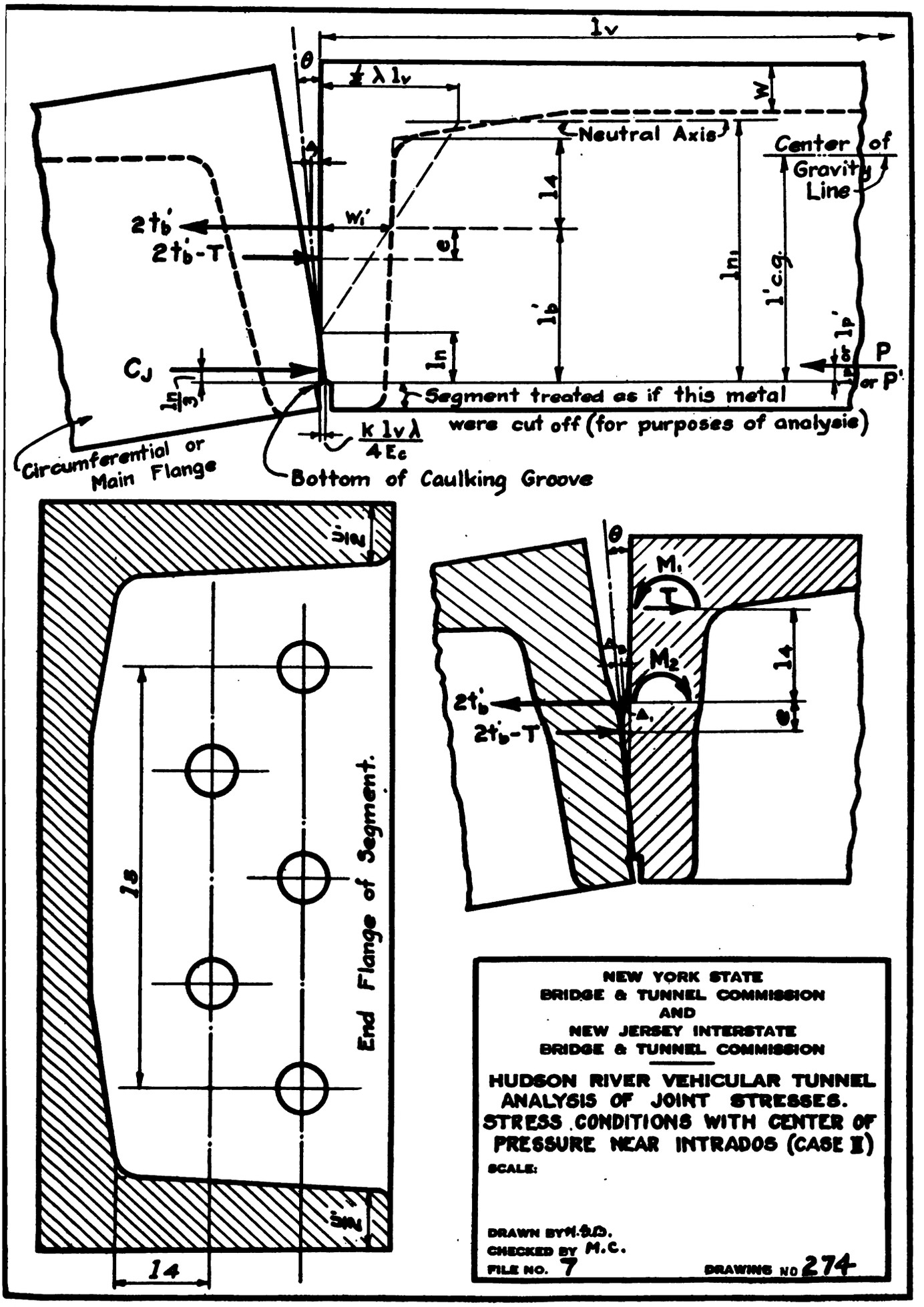
HUDSON RIVER VEHICULAR TUNNEL
ANALYSIS OF JOINT STRESSES
FORMULAE - CASE I.

SCALE:

DRAWN BY H.S.D.
CHECKED BY M.C.
FILE NO. 7 DRAWING NO. 273



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HUDSON RIVER VEHICULAR TUNNEL
ANALYSIS OF JOINT STRESSES.
STRESS CONDITIONS WITH CENTER OF PRESSURE NEAR INTRADOS (CASE I)

SCALE:

DRAWN BY M.S.D.
CHECKED BY M.C.
FILE NO. 7
DRAWING NO 274

CASE A $l_4\left[\sqrt{\frac{2\left(t_b'+\frac{\theta E_c I_1'}{l_4^2}\right)}{2t_b'-T}}-1\right] < l_b'$

$e = l_4\left[\sqrt{\frac{2\left(t_b'+\frac{\theta E_c I_1'}{l_4^2}\right)}{2t_b'-T}}-1\right]$

$M_1 = -2t_b' l_4 + (2t_b'-T)(l_4+e)\quad M_2 = (2t_b'-T)e$

$\Delta_1 = \frac{l_4^3}{3E_c I_1'}\left[\left(t_b'+\frac{\theta E_c I_1'}{l_4^2}\right)\sqrt{\frac{2\left(t_b'+\frac{\theta E_c I_1'}{l_4^2}\right)}{2t_b'-T}} - \left(t_b'+\frac{3\theta E_c I_1'}{l_4^2}\right)\right]$

CASE B $l_4\left[\sqrt{\frac{2\left(t_b'+\frac{\theta E_c I_1'}{l_4^2}\right)}{2t_b'-T}}-1\right] = l_b'$

$\Delta_B = \frac{e^3}{6E_c I_1'}\left[2t_b'-T\right]$

$e = l_b'$

$M_1 = -2t_b' l_4 + (2t_b'-T)(l_4+l_b');\quad M_2 = (2t_b'-T)l_b'$

CASE C $l_4\left[\sqrt{\frac{2\left(t_b'+\frac{\theta E_c I_1'}{l_4^2}\right)}{2t_b'-T}}-1\right] > l_b'$

$e = l_b'$

$M_1 = -2t_b' l_4 + (2t_b'-T)(l_4+l_b')\quad M_2 = (2t_b'-T)l_b'$

CASES A, B & C

$l_{n_1} = \frac{I' k_1}{M}$, $k_1 = \frac{P}{A} + \frac{M I'_{c.g.}}{I'}$, $M = P(l'_{c.g.} - l_p)$

T & θ assumed

e = (see above)

$l_n = 3\left[\frac{T(l_b'-e)+Pl_p+2t_b'e}{P+T}\right]$

Δ_1 = (see above)

$\theta = \frac{\Delta_1}{l_b'-l_n}$

$C_j = P+T$

$\lambda = \frac{2(l_{n_1}-l_n)C_j}{3 l_v G \theta U' l_n}$

$k = \frac{2C_j}{U' l_n} - k_1$

$l_n = \frac{k l_v \lambda l_b'}{4E_c\Delta_1 + k l_v \lambda}$

$t_b'-t_b = \frac{\Delta_B E_B A_B}{l_B'}$

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HUDSON RIVER VEHICULAR TUNNEL
ANALYSIS OF JOINT STRESSES
FORMULAE - CASE II

SCALE:

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FILE NO. 7
DRAWING NO. 275

Center of Relative Rotation

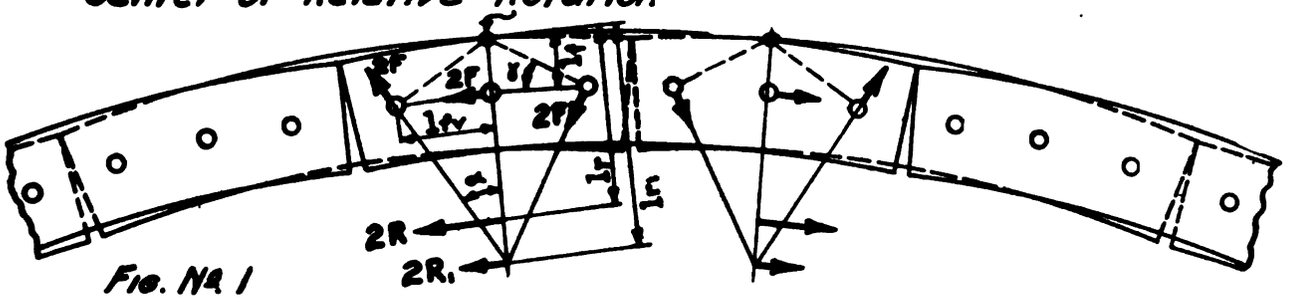

FIG. No. 1
SHOWING FRICTIONAL FORCES IN DETAIL

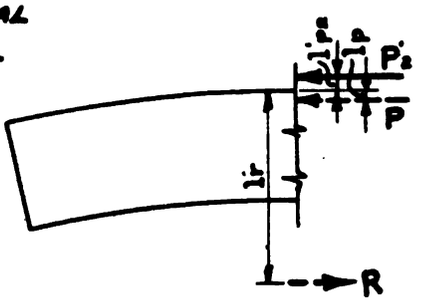

FIG. No. 2
SHOWING RESULTANT EFFECT OF FRICTIONAL FORCES AT CENTER OF SEGMENT

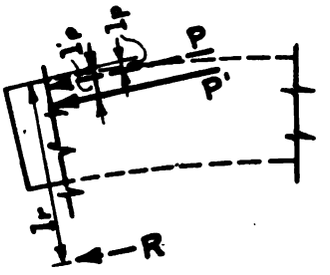

FIG. No. 3
SHOWING RESULTANT EFFECT OF FRICTIONAL FORCES AT THE JOINT

$F = t_c \mu$

$l_f = l_{cb}$ when l_n is small; $l_f = 0$ when l_n is large

$R = F(1 + 2 \sin. \alpha)$

$R_1 = F(2 \sin. \alpha)$

$l_{r_1} = l_f + l_{fv} \cot. \alpha$

$$l_r = \frac{F l_f + R_1 (l_f + l_{fv} \cot. \alpha)}{R}$$

$$= F\left[\frac{l_f (1 + 2 \sin. \alpha) + 2 l_{fv} \cos. \alpha}{F(1 + 2 \sin. \alpha)}\right]$$

$$= l_f + l_{fv}\left(\frac{2 \cos. \alpha}{1 + 2 \sin. \alpha}\right)$$

When l_n is small:

$P'_2 = P - R$

$l'_{p_2} = \dfrac{P l_p - R l_r}{P - R}$

$P' = P + R$

$l'_p = \dfrac{P l_p + R l_r}{P + R}$

When l_n is large:

$P'_2 = P$

$l'_{p_2} = \dfrac{P l_p - 2F l_{fv}}{P}$

$P' = P$

$l'_p = \dfrac{P l_p + 2F l_{fv}}{P}$

For Case II the center of Relative Rotation is at the Bottom of the Caulking Groove (see dwg. #274) when l_n is small. Using this Bottom of Caulking Groove as reference point of measurement, (as on dwg. #274) all above formulae remain unchanged.

l_f = Distance from gage line of Circumferential Bolts to Center of Rel. Rotation.

l_{cb} = Distance of Circumferential Bolts from Extrados.

t_c = Total tension in each Circumferential Bolt.

μ = Coefficient of friction for cast iron on cast iron.

$2R_1$ = Resultant of Frictional Forces excepting those due to bolts opposite Center of Rel. Rotation.

$2R$ = Resultant of all Frictional Forces.

($2R$ & $2R_1$ are for both circumferential flanges but for ½ the length of the segment only.)

P = Resultant thrust in the ring, action of circumferential bolts disregarded.

P' = Resultant thrust on Joint, action of circumferential bolts taken into account.

P'_2 = Resultant thrust at center of segment, action of circumferential bolts taken into account.

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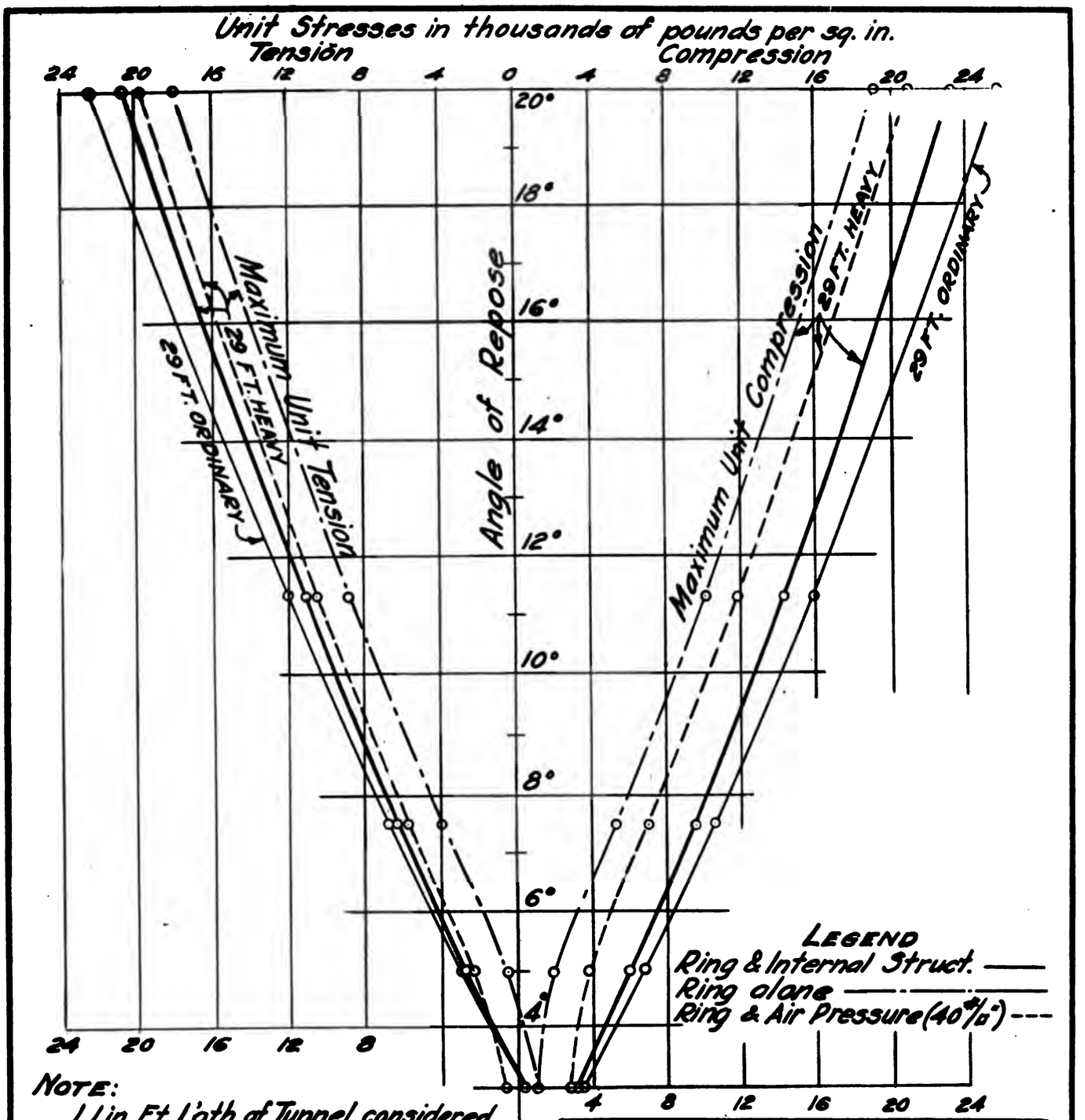
HUDSON RIVER VEHICULAR TUNNEL
ANALYSIS OF JOINT STRESSES
EFFECT OF CIRCUMFERENTIAL BOLTS
CASE I

SCALE:

DRAWN BY N.S.B.
CHECKED BY M.C.
FILE NO. 7
DRAWING NO. 276



NOTE:

1 Lin. Ft. L'gth of Tunnel considered.
38 ft. of Water on 31 ft. of silt to top of Tunnel.
Water @ 64#, silt @ 104# per cu. ft.
Air Pressure 40#/□" for 29 Cl. Tunnel.
True circular shape of tunnel assumed.
Conjugate earth pressures employed. (Rankine's Theory)
Cast Iron Segments alone are considered to withstand stresses.
Effect of Joints & adjacent Rings neglected.
For details of Ordinary & Heavy Segments see drawings #134 & #135 File #7.

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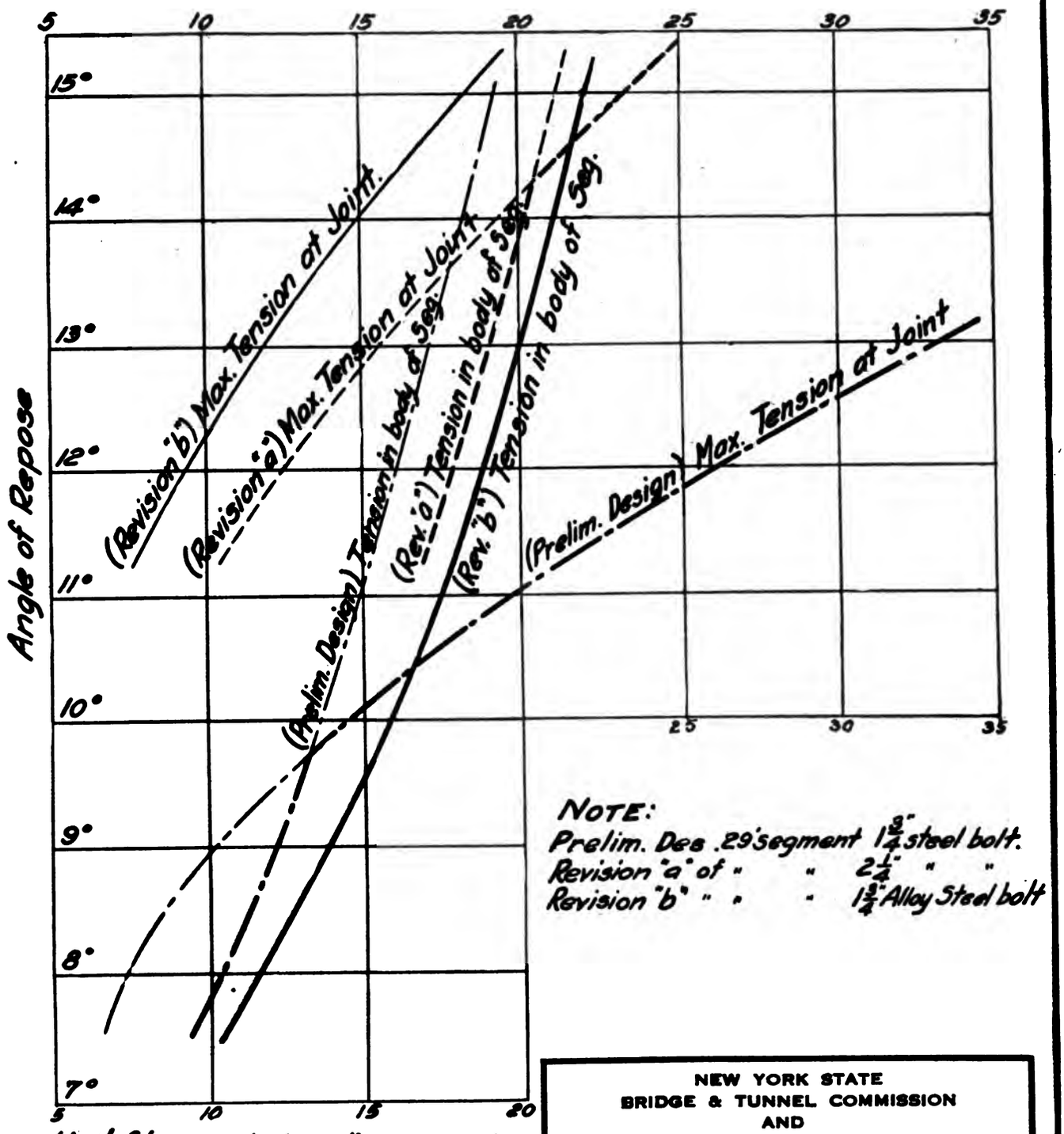
HUDSON RIVER VEHICULAR TUNNEL
29' CAST IRON TUNNEL
HEAVY & ORDINARY SECTIONS
COMPARATIVE STRESSES

SCALE: DATE

DRAWN BY
CHECKED BY
FILE NO. 7 DRAWING NO. 278



NOTE:
Prelim. Des. 29' segment 1 3/4" steel bolt.
Revision "a" of " " 2 1/4" " "
Revision "b" " " - 1 3/4" Alloy Steel bolt

Curves based upon elastic limit of:-
40000 #/□" for ordinary steel
80000 #/□" " alloy steel, bolts.
Bolts assumed stressed initially to elastic limit.
Heavy lines denote controlling stresses.
Maximum Tension at Joint occurs in segment near end flange.
Effect of Bolts & Joints considered.

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HUDSON RIVER VEHICULAR TUNNEL
29' DIA. CAST IRON TUNNEL HEAVY SECTION
PRELIMINARY DESIGN AND REVISIONS "a" & "b"
COMPARATIVE STRESSES

SCALE: DATE

DRAWN BY
CHECKED BY
FILE NO. DRAWING NO. 279

APPENDIX NO. 3

TUNNEL GASES INVESTIGATIONS—AMOUNT AND COMPOSITION OF AUTOMOBILE EXHAUST GASES

A. C. FIELDNER

CONTENTS

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Introduction	97
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PREFACE

The construction of the Vehicular Tunnel between New York and New Jersey under the Hudson River involves some problems in ventilation and design which have not heretofore been investigated. These problems arise from the substitution of automobiles and trucks for horse-drawn vehicles and the necessity of providing ventilation adequate for the removal of the exhaust gases.

The Chief Engineer of the Tunnel Commissions, Mr. Holland, asked the Bureau of Mines to take up the investigation regarding gases, as it was the only agency which had studied intensively, in cooperation with the U. S. Public Health Service, the physiological effects of carbon monoxide. Consideration was given as to whether the Bureau was justified in making an investigation concerning tunnels which did not relate directly to the extraction of minerals. The organic act establishing the Bureau calls not only for the mining, preparation, conservation, and utilization of minerals, but also for the investigation of mining methods and the safety and health of underground workers.

Ventilation is one of the most important problems as concerns both the safety and health of miners. No mining undertaking of any permanence can now disregard the necessity of having systematic ventilation and the problem is complicated by the presence of deleterious and poisonous gases. The most important of these gases — the one which causes most of the deaths resulting from asphyxia — is carbon monoxide. This insidiously poisonous gas is produced in great quantities by mine explosions and mine fires. The miner is daily exposed to small quantities of carbon monoxide through the use of explosives and in some mines from the exhaust of gasoline locomotives, pumps, hoists, or other types of internal combustion engines.

The problem of carbon monoxide poisoning is also one of great importance in metallurgical establishments in and around gas furnaces and gas producers. There has been much question concerning chronic effects on workers breathing small amounts of carbon monoxide in their daily tasks although the concentration is not usually sufficient to cause immediate difficulty and acute effects.

The subject as presented by the New York and New Jersey State Bridge and Tunnel Commissions to the Bureau of Mines therefore involved two important mining problems, viz., first the character and quantity of exhaust gases from internal combustion engines, and secondly the physiological effects of small quantities of carbon monoxide in the atmosphere and the amount that could safely be breathed for various intervals of time without injury to health.

Accordingly, with the approval of the Secretary of the Interior, the Bureau entered into cooperation with the New York and New Jersey State Bridge and Tunnel Commissions to conduct the investigation, the Bureau furnishing the laboratory facilities and the technical men for directing the inquiry, and the Tunnel Commissions furnishing the funds for the employment of technical assistance, labor, and supplies.

The investigations on problem one — the amount and character of the exhaust gas produced by various types and sizes of passenger cars and trucks — were conducted at the Pittsburgh Experiment Station under the direction of A. C. Fieldner, Supervising Chemist.

The investigations on problem two — the nature of the toxic substances in exhaust gas and their allowable concentration — were conducted in the physiological laboratory of Yale University under the direction of Dr. Yandell Henderson, Professor of Physiology and Consulting Physiologist of the Bureau of Mines, with the aid of a staff of physiologists and chemists employed by the Bureau for this purpose. Acknowledgment is due to Yale University for cordial and efficient cooperation in carrying out these investigations.

The results herein reported are believed to be of inestimable value not only for the New York and New Jersey tunnel and similar undertakings in different parts of the country, but also in general for mines and metallurgical establishments. I consider it a very excellent piece of scientific work and a credit to all concerned, and especially to my predecessor, Dr. Van H. Manning, under whose administration the work was organized and carried on.

(Signed) F. G. COTTRELL

Director, Bureau of Mines.

SUMMARY REPORT ON THE AMOUNT AND COMPOSITION OF THE EXHAUST GASES FROM MOTOR VEHICLES IN RELATION TO THE VENTILATION OF VEHICULAR TUNNELS

by

A. C. Fieldner, Supervising Chemist, A. A. Straub, Mechanical Engineer, and G. W. Jones, Assistant Physical Chemist

INTRODUCTION

The investigation summarized in this report was undertaken in cooperation with the New York and New Jersey State Bridge and Tunnel Commissions for the purpose of determining the average amount and composition of the exhaust gases from motor vehicles under operating conditions similar to those that will prevail in the Hudson River Vehicular Tunnel. A comprehensive set of road tests upon 101 motor vehicles including representative types of passenger cars and trucks was conducted at the Pittsburgh Experiment Station of the Bureau of Mines in accordance with a program laid out by the Chief Engineer of the Tunnel Commissions. The tests were started on December 1, 1919, and were completed on September 30, 1920, thus covering both winter and summer operating conditions. The cars tested were taken at random from those offered by private individuals, corporations, and automobile dealers of Pittsburgh; and the tests were made without any change in carburetor or other adjustment. The results may therefore be taken as representative of motor vehicles as they are actually being operated on the streets at the various speeds and grades that will prevail in the tunnel.

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The authors take pleasure in acknowledging the inspiration and support received from Dr. Van H. Manning, former Director of the Bureau of Mines, who appreciated the public need of research on tunnel ventilation problems, and the hearty cooperation of Mr. C. M. Holland, Chief Engineer of the New York State Bridge and Tunnel Commission and the New Jersey Interstate Bridge and Tunnel Commission, who initiated this investigation. Mr. Holland and his staff, in particular, Mr. O. Singstad, Designing Engineer, and Mr. A. C. Davis, Mechanical Engineer, gave especial assistance by furnishing an outline of automobile and truck tests required to simulate the conditions of speed and grade which would prevail in the Hudson River Vehicular tunnel.

Acknowledgment is due George S. Rice, Chief Mining Engineer, and O. P. Hood, Chief Mechanical Engineer, of the Bureau of Mines, for frequent consultation and advice. E. A. Holbrook, Superintendent, R. H. Kudlich, Mechanical Engineer, J. D. Davis, Chemist, and other members of the staff of the Pittsburgh Experiment Station aided in the experimental work.

The automobiles and trucks tested were generally lent the Bureau of Mines by public-spirited citizens, automobile dealers and corporations of Pittsburgh, through the aid of the Chamber of Commerce, the Pittsburgh Automobile Club, and the Automobile and Truck Dealers Association.

TYPES OF MOTOR VEHICLES TESTED

The selection of types of motor vehicles for tests is based on traffic counts taken at the ferries across the Hudson River. All the cars tested are listed in tables 1 to 6, where they are arranged in six classes as follows:

Class	Description	No. of Cars Tested
1	Five-passenger	19
2	Seven-passenger	13
3	Trucks up to one and one-half tons	12
4	Trucks, one and one-half to three tons inclusive	22
5	Trucks, three and one-half to four tons inclusive	17
6	Trucks, five tons and over	18
Total		101

Twenty-four cars were tested under winter conditions between December 1st, and February 6th; seventy-seven cars were tested under spring and summer conditions between March 11 and September 30, 1920.

Description of motor vehicles tested is given in tables 1 to 6 inclusive.

TABLE 1

DESCRIPTION OF MOTOR VEHICLES TESTED

Class 1 — Five-passenger Cars

Car Number	Make	Date of Test	Car Body	Number of Cyls.	Size of Cylinders	Rated Horse-power	Weight of Car
			WINTER TESTS				
20	A	January 13, 1920	Touring	4	3¾ x 4	22.5	1,900
21	A	January 13, 1920	Touring	4	3¾ x 4	22.5	1,900
6	B	December 16, 1919	Touring	4	3 11/16 x 4	21.8	2,000
12	B	December 29, 1919	Touring	4	3 11/16 x 4	21.8	2,010
1	C	December 3–4, 1919	Touring	4	3⅞ x 4½	24.0	2,525
9	C	December 22–23, 1919	Touring	4	3⅞ x 4½	24.0	2,545
16	C	January 6, 1920	Touring	4	3⅞ x 4½	24.0	2,700
8	D	December 18–19, 1919	Touring	4	3⅜ x 5	18.2	2,700
7	E	December 18, 1919	Touring	6	3½ x 5	29.4	3,150
13	F	January 23, 1920	Touring	6	3⅜ x 4½	27.3	3,300
18	F	January 9–10, 1920	Touring	6	3⅜ x 4½	27.3	3,400
			SUMMER TESTS				
43	A	May 5, 1920	Sedan	4	3¾ x 4	22.5	2,050
42	M	May 4, 1920	Touring	4	3⅜ x 4½	22.0	2,250
99	C	September 27, 1920	Touring	4	3⅞ x 4½	24.0	2,525
55	N	May 25–26, 1920	Touring	6	3¼ x 4	25.3	2,725
44	D	May 6, 1920	Touring	4	4⅛ x 4½	27.2	2,920
81	O	July 26, 1920	Touring	4	3⅜ x 5	18.2	2,955
29	P	March 24, 1920	Roadster	4	4⅛ x 4½	27.2	3,000
53	F	May 21, 1920	Touring	6	3⅜ x 4½	27.3	3,300

TABLE 2

DESCRIPTION OF MOTOR VEHICLES TESTED

Class 2 — Seven-passenger Cars

Car Number	Make	Date of Test	Car Body	Number of Cyls.	Size of Cylinders	Rated Horse-power	Weight of Car
			WINTER TESTS				
15	G	January 5–6, 1920	Touring	6	3½ x 5	29.4	3,600
10	G	December 23–24, 1919	Touring	6	3½ x 5	29.4	3,700
11	G	December 26–27, 1919	Sedan	6	3½ x 5	29.4	3,925
23	H	February 2, 1920	Touring	8	3⅛ x 5½	31.2	4,350
3	I	December 8–9–10, 1920	Touring	12	3 x 5	43.2	4,851
4	I	December 12, 1919	Touring	12	3 x 5	43.2	5,000
14	I	January 5–7, 1920	Touring	12	3 x 5	43.2	5,000
			SUMMER TESTS				
91	G	August 16, 1920	Touring	6	3½ x 5	29.4	3,600
49	Q	May 14, 1920	Touring	8	3 x 5	28.8	4,250
62	H	June 11, 1920	Touring	8	3⅛ x 5½	31.3	4,600
63	H	June 14, 1920	Touring	8	3⅛ x 5½	31.3	4,980
51	I	May 18, 1920	Touring	12	3 x 5	43.2	5,175
52	I	May 20, 1920	Touring	12	3 x 5	43.2	5,200

TABLE 3

DESCRIPTION OF MOTOR VEHICLES TESTED

Class 3 — Trucks up to One and one-half Tons Capacity

Car Number	Make	Date of Test	Car Body	Number of Cyls.	Size of Cylinders	Rated Horse-power	Weight of Car
			WINTER TESTS				
5	J	December 15–16, 1919	Truck	4	3¾ x 4	22.5	1,850
22	J	January 14–15, 1920	Delivery	4	3¾ x 4	22.5	1,850
19	J	January 12–13, 1920	Express	4	3¾ x 4	22.5	3,000
2	K	December 5–6, 1920	Delivery	4	3¾ x 5½	22.5	3,925
17	K	January 20–21, 1920	Bus	4	3¾ x 5½	22.5	4,800
			SUMMER TESTS				
47	R	May 12, 1920	Delivery	6	2 13/16 x 4¾	19.0	2,575
84	S	July 30, 1920	Delivery	4	3 11/16 x 5½	21.0	3,700
76	T	July 14, 1920	Chassis	4	3½ x 5½	19.6	3,725
68	L	June 26, 1920	Chassis	4	3¾ x 5½	22.5	3,850
89	U	August 12, 1920	Delivery	4	3½ x 5	19.6	3,939
75	T	July 12, 1920	Express	4	3½ x 5½	19.6	4,325
60	L	June 9, 1920	Delivery	4	3¾ x 5½	22.4	4,550

TABLE 4

DESCRIPTION OF MOTOR VEHICLES TESTED

Class 4 — Trucks One and one-half to Three Tons Capacity, Inclusive

Car Number	Make	Date of Test	Car Body	Number of Cyls.	Size of Cylinders	Rated Horse-power	Weight of Car
79	AA	July 21–22, 1920	Dump	2	4½ x 4¾	18.0	4,200
82	BB	July 27–28, 1920	Chassis	4	3¾ x 5	22.5	4,350
71	BB	July 1, 1920	Chassis	4	3¾ x 5	22.5	4,500
74	TT	July 9–10, 1920	Chassis	4	3½ x 5½	19.6	4,600
86	UU	August 4, 1920	Chassis	4	4 x 5½	25.6	4,700
77	CC	July 15–16, 1920	Chassis	4	4½ x 5½	27.2	4,700
67	LL	June 23–24, 1920	Chassis	4	3¾ x 5½	22.5	5,225
78	AA	July 20, 1920	Delivery	2	4½ x 4¾	18.0	5,275
87	UU	August 5–6, 1920	Chassis	4	4 x 5½	25.6	5,575
83	DD	August 29, 1920	Dump	4	3¾ x 5½	22.5	5,750
73	TT	July 8, 1920	Dump	4	4 x 5	25.6	6,100
28	II	March 22, 1920	Chassis	4	5 x 5½	40.0	6,200
88	KE	August 10, 1920	Chassis	4	4½ x 5½	27.2	6,375
85	KE	August 3–4, 1920	Chassis	4	4½ x 5½	27.2	6,375
33	FF	April 1–2, 1920	Chassis	4	4½ x 5½	27.2	6,400
80	GG	August 23–24, 1920	Chassis	4	4½ x 5½	27.2	6,500
32	HH	March 31, 1920	Dump	4	4½ x 5½	27.2	6,600
50	JJ	May 17–18, 1920	Dump	4	4½ x 5½	28.9	7,200
37	KK	April 21–22, 1920	Ammunition	4	4¾ x 5½	36.2	8,350
39	MM	April 26–27, 1920	Army	4	4¾ x 6	36.2	10,700
46	MM	May 11, 1920	Army	4	4¾ x 6	36.2	11,000
38	MM	May 23, 1920	Army	4	4¾ x 6	36.2	11,725

TABLE 5

DESCRIPTION OF MOTOR VEHICLES TESTED

Class 5 — Trucks Three and one-half to Four and one-half Tons Capacity, Inclusive

Car Number	Make	Date of Test	Car Body	Number of Cyls.	Size of Cylinders	Rated Horse-power	Weight of Car
			WINTER TEST				
24	I	February 2, 1920	Dump	4	4½ x 5	32.4	9,650
			SUMMER TESTS				
90	UU	August 13–14, 1920	Chassis	4	4 x 5½	25.6	5,875
31	HH	March 29–30, 1920	Chassis	4	4½ x 5½	32.4	6,670
58	NN	June 4–5, 1920	Chassis	4	4½	32.4	6,950
27	OO	March 17–18, 1920	Chassis	4	4½ x 5	32.4	7,100
34	FF	April 5–6, 1920	Chassis	4	4½ x 5½	32.4	7,600
26	OO	March 15–16, 1920	Chassis	4	4½ x 5½	32.4	7,750
66	LL	June 21, 1920	Chassis	4	3¾ x 5¾	22.5	7,800
92	PP	August 18–19, 1920	Chassis	4	4½ x 6	32.4	7,950
97	PP	September 9, 1920	Chassis	4	4½ x 6	32.4	8,250
70	QQ	June 30, 1920	Chassis	4	4¼ x 5½	28.9	8,500
72	QQ	July 3–6, 1920	Chassis	4	4¼ x 5½	28.9	8,500
57	RR	June 2–3, 1920	Chassis	4	4½ x 5½	32.4	9,300
98	SS	September 10–11, 1920	Chassis	4	5 x 6	40.0	9,350
35	VV	April 14, 1920	Dump	4	4½ x 6½	32.4	9,400
41	VV	May 3, 1920	Dump	4	4½ x 6½	32.4	9,400
95	LL	August 25–26, 1920	Dump	4	3¾ x 5¾	22.5	10,350

TABLE 6

DESCRIPTION OF MOTOR VEHICLES TESTED

Class 6 — Trucks Five-ton and over Capacity

Car Number	Make	Date of Test	Car Body	Number of Cyls.	Size of Cylinders	Rated Horse-power	Weight of Car
25	OO	February 11–12, 1920	Chassis	4	4½ x 5½	32.4	8,700
65	LL	June 16–17–18, 1920	Chassis	4	4¼ x 5¾	28.8	8,900
56	VV	May 27–28, 1920	Chassis	4	4½ x 5½	32.4	9,500
54	II	May 24–25, 1920	Chassis	4	5 x 5½	40.0	9,675
30	HH	March 25–26, 1920	Chassis	4	4¾ x 6	36.1	10,000
40	SS	April 28–29, 1920	Army	4	5 x 6	40.0	10,925
36	WW	April 15–16, 1920	Dump	4	4⅞ x 5½	38.0	11,000
48	SS	May 13, 1920	Lumber delivery	4	4¼ x 6¾	29.0	11,220
59	WW	June 7–8, 1920	Dump	4	4⅞ x 6	38.0	11,350
64	SS	June 16, 1920	Dump	4	5 x 6	40.0	11,450
93	WW	August 20, 1920	Dump	4	4⅞ x 6	38.2	11,500
45	VV	May 10, 1920	Dump	4	4½ x 6½	32.4	11,550
61	WW	June 10, 1920	Dump	4	4⅞ x 6	38.2	11,920
69	II	June 28–29, 1920	Dump	4	5 x 5½	40.0	11,950
94	CC	August 23–24, 1920	Dump	4	4¾ x 6½	36.2	12,450
96	SS	September 7–8, 1920	Dump	4	5 x 6	40.0	13,200
100	SS	September 27–28, 1920	Dump	4	5 x 6	40.0	12,350
101	SS	September 29–30, 1920	Dump	4	5 x 6	40.0	12,350

CONDITIONS OF TEST

In the winter series, all cars were tested under the following conditions:

Car standing, engine racing.

Car standing, engine idling.

Car accelerating from rest to fifteen miles per hour up 3 per cent grade.

Car running fifteen, ten, and three miles per hour up 3 per cent grade.

Car running fifteen, ten, and three miles per hour down 3 per cent grade.

Car accelerating from rest to fifteen miles per hour on level grade.

Car running fifteen, ten and three miles per hour on level grade.

In the summer series the general test conditions were simplified by omitting the racing, idling and accelerating tests in most cases; sufficient data was obtained in the winter tests to show that these particular test conditions were of minor importance in estimating the total quantity of carbon monoxide generated in the tunnel; a six mile per hour test was substituted for the three mile per hour test as being more representative of slow-moving traffic; and a 20-mile per hour test on level grade was added for passenger cars; the remaining tests were the same as in the winter series. Most of the heavy trucks were tested at six and ten miles per hour only, as they could not be speeded to fifteen miles per hour.

Trucks and seven-passenger cars were tested with full load at rated capacity and also with no load other than the two observers, chauffeur, and apparatus (weighing fifty pounds). Five-passenger cars were tested with the light load only, consisting of three men and apparatus. The summary tables giving results of tests are averages of the light and loaded tests.

MANNER OF CONDUCTING TESTS

Description of car:

On receiving a car for test, a complete description of the car, motor, tires, accessories, oil and gasoline used, was recorded. The gasoline feed pipe was disconnected at the carburetor and the gasoline measuring apparatus was connected in its place. This apparatus was supplied with the same brand of gasoline as was being used in the car. The exhaust gas sampling apparatus was then

put in place and the motor was allowed to run until it became warmed up to the normal running temperature.

Tests with motor racing and idling:– With the throttle and spark set so that the motor raced, the test was started when the gasoline level in the measuring tube reached the zero or starting point. The time interval of the test, measured by stop-watch, was contingent on the quantity of gasoline consumed necessary to minimize errors of measurement, and on the time necessary for collecting a representative gas sample. The gas sample was drawn at a uniform rate throughout the test as more fully described under method of sampling exhaust gases. The test with motor idling was conducted in a similar manner.

Road tests on 3 per cent grade:– The car was next driven to the three per cent grade course, which was one mile long and marked off in quarter mile distances.

Acceleration from rest to fifteen miles per hour up grade:– The car was brought to a stop with motor running at the first quarter mile work, where the grade was 3.4 per cent. On signal from the test engineer the car was started in low gear, accelerated, and gears shifted until the car was running on high gear at fifteen miles per hour. The car was then stopped as quickly as possible without sliding the wheels, by throwing out the clutch and putting on the brakes. The same operation was repeated as often as possible for a distance of one-half mile. This repeated acceleration was required to consume an accurately measurable quantity of gasoline and to provide a representative gas sample.

At the moment of starting the car on the quarter-mile mark, the test engineer started his stop-watch, switched off the gasoline from reserve supply and turned on the gasoline from the measuring tube, while the other observer simultaneously began collecting the exhaust gas sample. On crossing the finish mark of the course the stop-watch was stopped, the gasoline feed switched from the measuring tube to the reserve supply and the gas sample tube was closed. One man gave his entire attention to collecting the gas sample at a uniform rate so that the sample container was completely filled with exhaust gas at the end of the test.

Car running fifteen, ten and three or six miles per hour up and down 3 per cent grade:– In the uniform speed tests the car was driven across the starting point at the designated rate of speed as indicated by the speedometer. On crossing the starting line the stop-watch, gasoline feed from measuring tube, and exhaust gas sample were started simultaneously. The speed of the car and the rate of collecting the gas sample were checked at each quarter-mile mark and slight corrections made if required. On crossing the finish mark the stop-watch was stopped, the gasoline supply was shut off, and the gas sample tube was closed. The car was then stopped and the gasoline measuring apparatus leveled, read and refilled to the zero mark for the down grade test at the same speed.

Accelerating and three miles per hour tests were made over a half-mile course from the quarter-mile mark to the three-quarter mile mark; all other tests were one mile in length. The average grade of the half-mile tests is 3.32 per cent and for the one mile tests, 2.79 per cent.

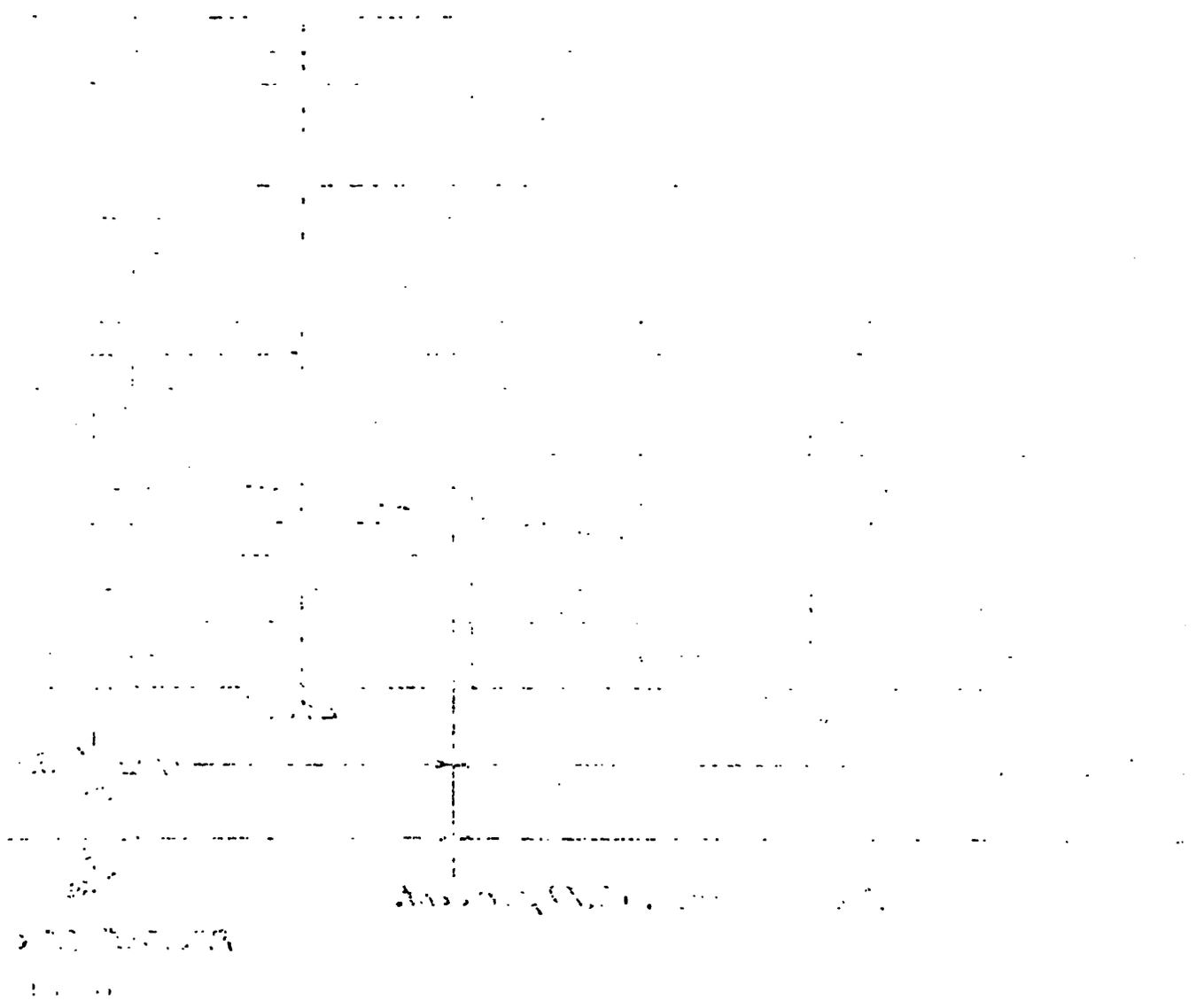
Car running twenty, fifteen, ten and six and three miles per hour on level grade:– The level grade tests were made in the same manner as the three per cent grade tests, on a one mile course having an average grade of 0.08 per cent.

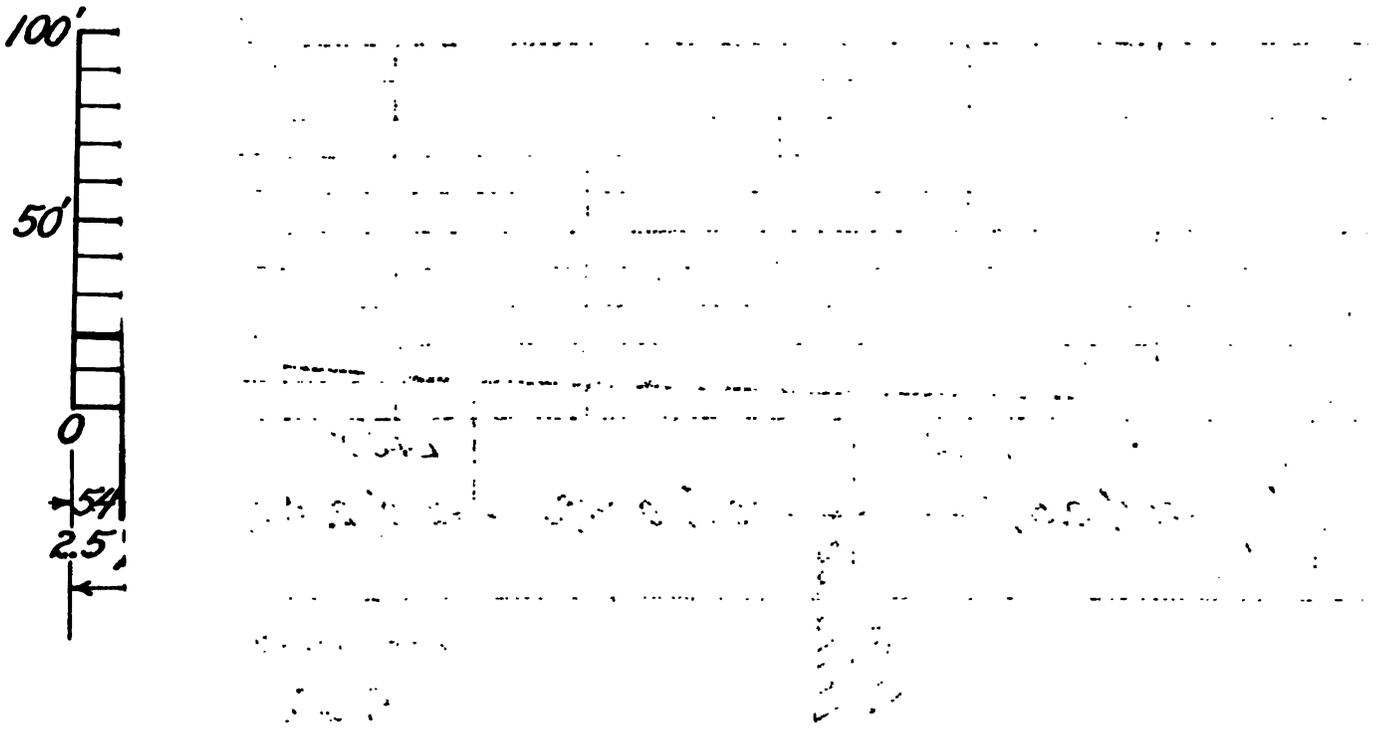
The driver of the car was allowed to use his own judgment on the position of the spark, the use of air-choke, dash carburetor adjustment, use of foot accelerator on hand throttle; his only instruction was to maintain the designated speed as uniformly as possible.

Description of Test Courses

Three per cent grade:– Profile and plan of the 3 per cent grade course are shown in figures 1 and 2 respectively. All the streets in this course were paved with asphalt in excellent condition. While there was a fair amount of traffic, no trouble was experienced from stoppage by other vehicles due to the absence of much traffic on the few intersecting streets.

Level course:– Figures 3 and 4 are profile and plan of the level course also one mile long. The Stanton Avenue portion of this course outside of Highland Park was asphalt in good condition; the remainder of the course in the park was macadam in rather bad condition. There were no deep holes, but the surface as worn and uneven.

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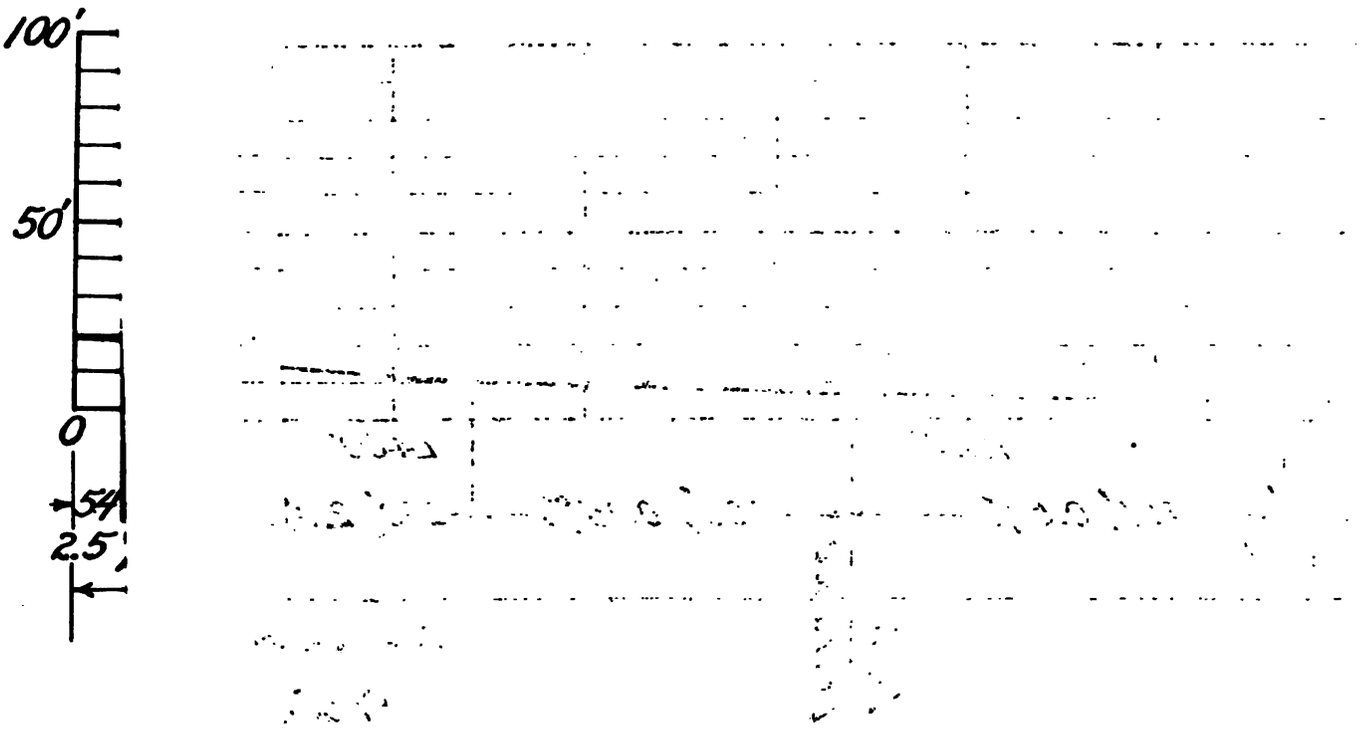
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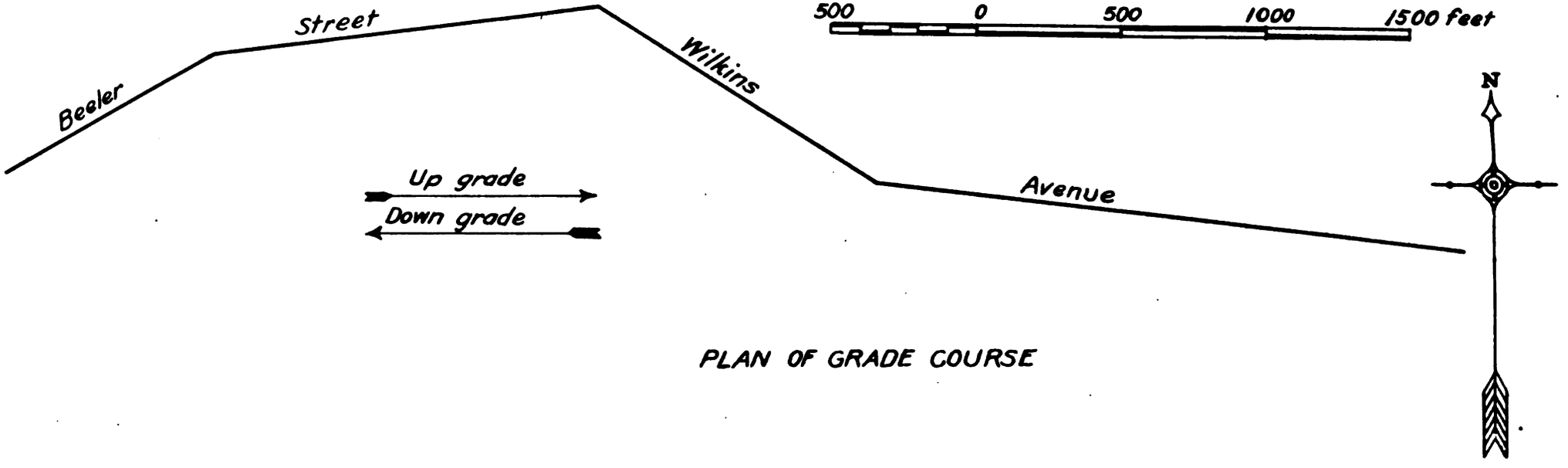
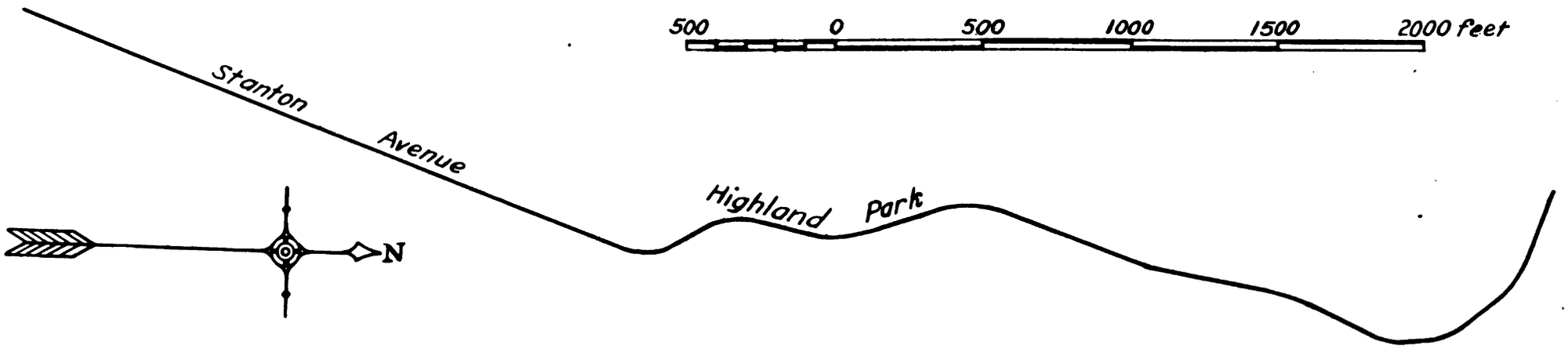


PLAN OF GRADE COURSE

Figure 2



PLAN OF LEVEL COURSE

Figure 4

METHOD OF SAMPLING EXHAUST GASES

Method of sampling:—Twenty-five exhaust gas samples were taken in the course of testing a single car, both loaded and light under winter conditions. For tests under summer conditions this number was somewhat reduced, depending upon the type of car or truck tested. Each was a continuous sample representing the average composition of the exhaust gas during a single test condition as for example, condition "d", car running at a uniform speed of fifteen miles per hour up a 3 per cent grade one mile long.

The apparatus used for taking the gas samples is shown in Figure 5. The sampling tube, g, of one-quarter or five-sixteenths inch copper tubing, dependent upon size of car or truck, was introduced in the exhaust manifold through which the exhaust gases from all the cylinders were passing before entering the muffler, with the opening, f, turned directly against the flow of gases. A gas tight fit was obtained by using a bushing and clamp around the exhaust pipe. The copper tube extended back along the exhaust pipe, to prevent freezing of moisture, and up through the floor of the car where connection was made to a one-quarter inch heavy walled rubber tube, *h*, which is connected to the glass tee, *a*. The main stream of exhaust gases passed on through the rubber tube *b*, and were discharged into the atmosphere through the water seal, *c*, thus preventing any air from being sucked back into the sample. With the engine running under test conditions, a steady and rapid stream of gas flowed out at the water seal. The pulsations of the engine were largely damped by the length of tubing used. Smoke observations were taken at the water seal, *d*.

The gas sample containers or "sampling tubes," *K*, were of 250 cc. capacity, and were made of glass tubing about one and one-half inches in diameter, drawn out and sealed to capillary tubes to fit a five-sixteenths inch rubber tube at each end. The rubber connections were carefully wired gas tight. Heavy walled composition rubber tubing was found best adapted for use with the screw clamp which regulated the rate of discharge of the water from the lower end of the container, and three-sixteenths inch pure gum rubber tubing was found to give a gas tight seal with a strong spring clamp at the upper end of the container.

The sample containers were completely filled in the laboratory with water containing 5 per cent sodium chloride and saturated with exhaust gases to reduce solubility of carbon dioxide, and were transported in two wood carrying cases as shown in Plate 1. The water filled container was attached to the tee, *a*, (Figure 5) by slipping the pure gum tubing moistened with water over the lower branch of the tee, and was held in place on the board by two rubber bands as shown in Figure 5. The gas sample was then taken continuously over the whole period of a given test, by opening the upper pinch clamp and the screw clamp on the lower end of the container and adjusting it to allow the container to becom empty at the exact time for terminating the test. The water flowed into the jar, *e*, and this water was returned to the laboratory for refilling other sample containers. One observer gave his entire attention to taking the gas samples and regulating the flow of water from the gas sample container by readjusting the screw clamp at regular intervals, so that all the water was displaced by gas at the end of the test. No water remained in contact with the gas other than that adhering to the walls and the few drops that remained in the capillary ends of the container.

METHODS OF ANALYZING EXHAUST GASES

All gas samples were analyzed in duplicate, by two different analysis and on two different apparatus, determining carbon dioxide (CO_2) oxygen (O_2), carbon monoxide (CO), hydrogen (H_2), methane, (CH_4) and nitrogen (N_2). As the rubber tubing on the ends of the gas sample containers are not entirely impervious to gases, especially hydrogen, the analyses were made promptly after the tests. Samples that had to be kept more than eight or ten hours were kept under water to prevent diffusion through the rubber.

The modified Orsat gas analysis apparatus used in analyzing the exhaust gases is shown in Plate 2 and Figure 6. It is similar in principle to the apparatus used by Burrell and

Plate No. 1

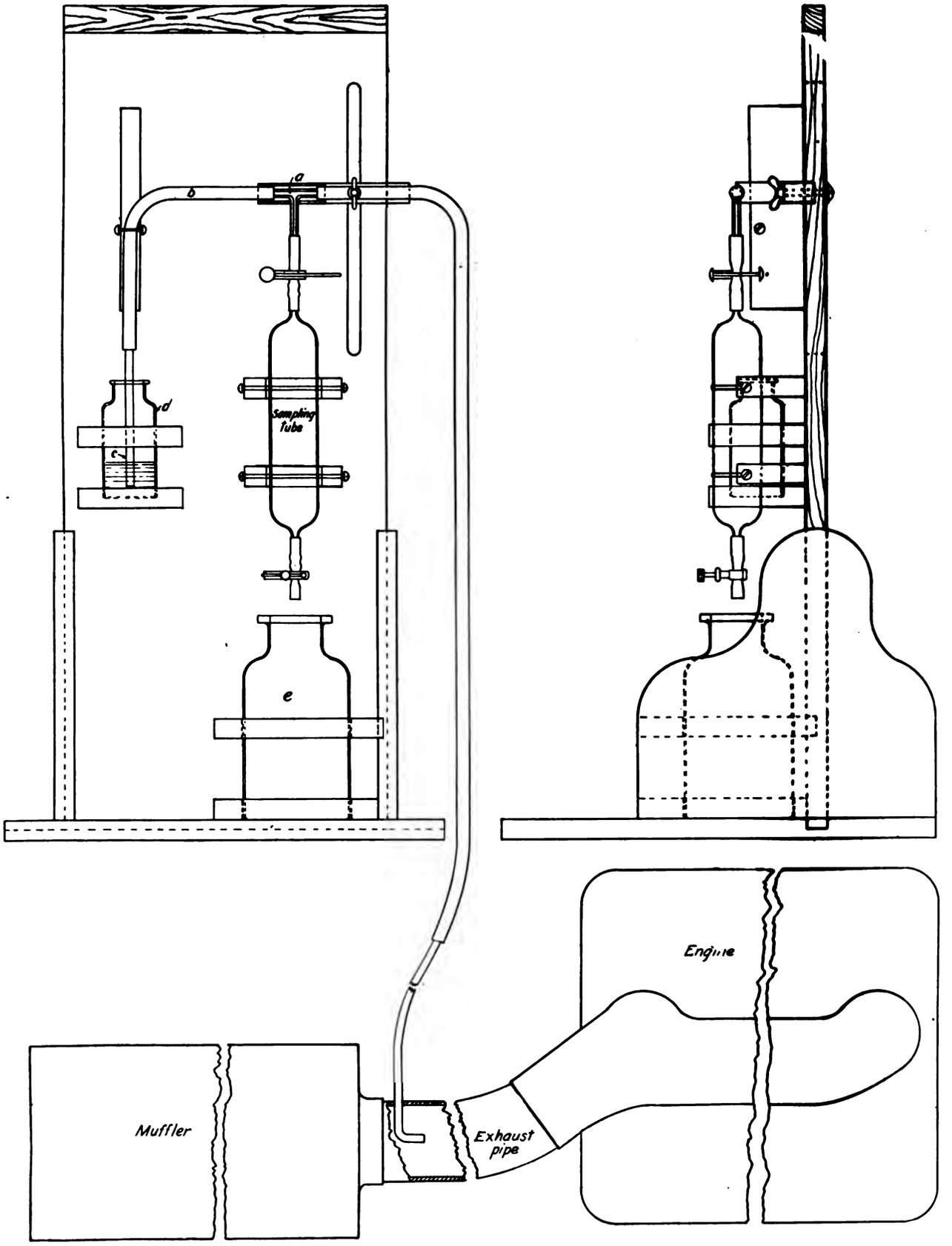


Figure 5

Seibert.* The carbon dioxide was absorbed in potassium hydroxide solution; the oxygen in potassium pyrogallate; the carbon monoxide in two bubbling pipettes in series containing acid cuprous chloride solution; and the hydrogen, methane and any residual carbon monoxide were determined by slow combustion in the presence of a hot platinum wire. Mercury was used in the burette, slow combustion pipette and for displacing the gas from the sample container.

INTERPRETATION OF EXHAUST GAS ANALYSES

The gaseous constituents from automobile engines are carbon dioxide, oxygen, carbon monoxide, hydrogen, methane, gasoline vapor, nitrogen, and traces of unsaturated hydro-carbons.

Carbon dioxide:—Carbon dioxide is formed by complete combustion of carbonaceous material. The amount of carbon dioxide in exhaust gas depends on a number of factors, chief of which are ratio of air to gasoline vapor, (carburetor adjustment), thoroughness of mixing vapor and air, completeness of vaporization, temperature and degree of compression in the cylinders. Under ideal conditions with the theoretical amount of air for perfect combustion of the gasoline, the only products of the reaction or combustion should be carbon dioxide, water vapor, and nitrogen. The nitrogen comes from the air used for combustion. If an excess of air is present, the combustion products are carbon dioxide, water vapor, oxygen and nitrogen. However, under practical operating conditions, there is usually a small percentage of oxygen passing through into the exhaust gases even when a definiency of air is mixed with the gasoline vapors. The maximum possible percentage of carbon dioxide is formed in the exhaust gas when the theoretical amount of air is present and there is perfect combustion of the hydrogen and carbon of the gasoline. This value varies slightly with the percentages by weight of carbon and hydrogen in the gasoline. Assuming a gasoline of eighty-four per cent carbon and sixteen per cent hydrogen, then

	CO_2 lbs.	H_2O lbs.	N_2 lbs.
.84 lb. carbon produces	3.08	....	7.43
.16 lb. hydrogen produces	....	1.44	4.25
Total	3.08	1.44	11.68

The water condenses out and is not indicated in the exhaust gas analysis. Changing from a weight to a volumetric basis, by dividing by the molecular weights:

$$\frac{11.68}{28} = .417$$

$$\frac{3.08}{44} = .070$$

Total .487

$\frac{.070}{.487} \times 100 = 14.4\%$, carbon dioxide by volume.

$\frac{.417}{.487} \times 100 = 85.6\%$, nitrogen by volume.

Fourteen and four-tenths per cent is the maximum carbon dioxide content that can be obtained in the exhaust gases when the above gasoline is used. When the exhaust gas indicates this value for carbon dioxide, the combustion is perfect. Lower values are due either to incomplete combustion or excess air.

Oxygen:—Oxygen in the gases may be due to excess air (lean mixture), a large excess of gasoline vapor (very rich mixture), incomplete vaporization, or poor mixing of the gasoline vapor and air in the engine. If the gasoline is not completely vaporized and is partly carried into the cylinder

* Burrell, G. A., and Seibert, F. M., The Sampling and Examination of Mine Gases and Natural Gas; Bureau of Mines, Bulletin 42, 1913, p. 43.

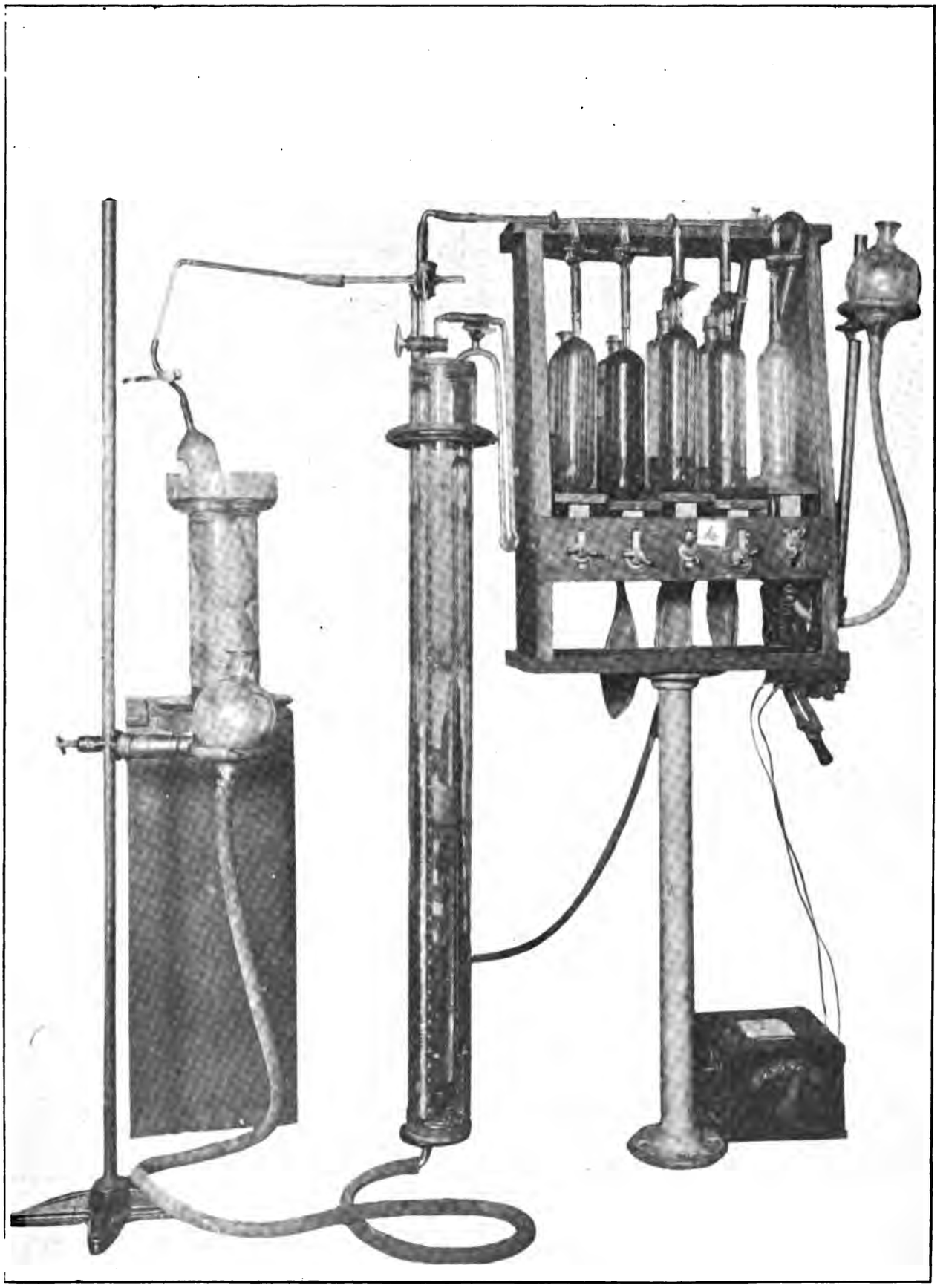


PLATE 2. ORSAL APPARATUS AND SAMPLE CONTAINER CONNECTED READY FOR ANALYSIS OF GAS SAMPLE

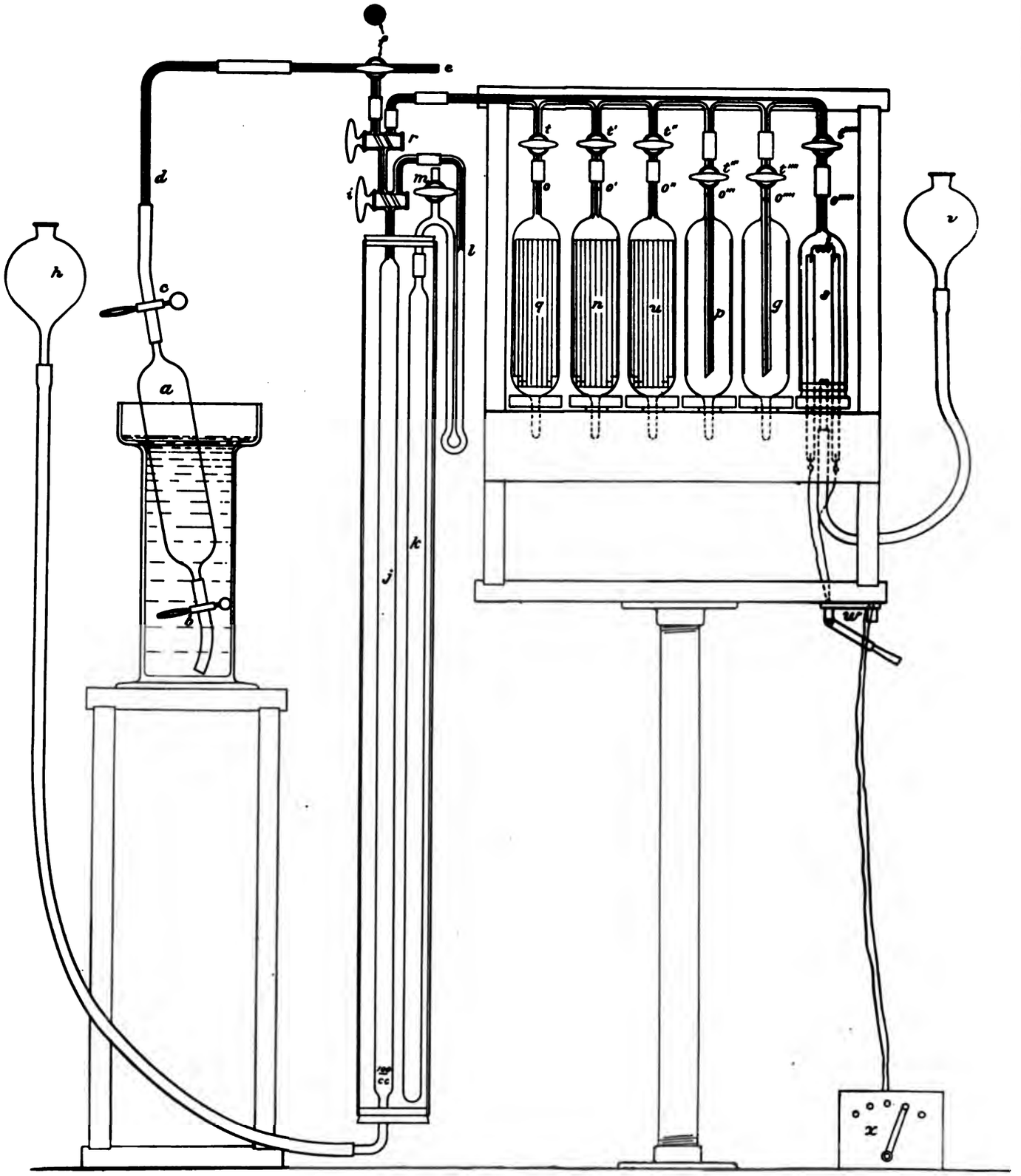


Figure 6

in the form of a mist consisting of small globules of liquid gasoline, the combustion is incomplete, especially at low speeds and before the engine gets warmed up. The oxygen cannot get at all the gasoline in the interior of these particles in the short time interval of the explosion in the cylinder. This condition gives free oxygen in the exhaust gases together with large percentages of incomplete combustion products as carbon monoxide, hydrogen and methane.

Carbon Monoxide:—Carbon monoxide, the poisonous constituent of exhaust gases, is formed by incomplete combustion of carbon. Unless an excess of air is present and the gases are perfectly vaporized and mixed, carbon monoxide is produced in varying large quantities. Carburetor adjustment for feeding a rich mixture is the most general cause for the large quantities of carbon monoxide formed in the exhaust of most machines. The mixture may be so rich that the ignition takes place only in the neighborhood of the spark and does not propagate itself throughout the whole charge. This condition produces large amounts of carbon monoxide and other unburned gases, such as hydrogen and methane, together with oxygen and gasoline vapor. Experiments made by Burrell* showed that when a mixture of 5 per cent gasoline-vapor in air was exploded, 9 per cent of unconsumed oxygen remained in the residual gases, and the flame traveled so slowly that it could be followed by the eye. When 4.1 per cent gasoline-air mixture were exploded there was found 3.4 per cent of oxygen. This substantiates the fact that when rich mixutres are used in gasoline engines there may be large quantities of oxygen present in the exhaust gases accompanied by products of incomplete combustion.

The presence of carbon monoxide in automobile exhaust gases is not only objectionable on account of its poisonous nature, but it means a material loss in mileage per gallon of gasoline used. The average analysis of exhaust gas from the 101 cars and trucks tested in this investigation showed about 6.5 per cent carbon monoxide. This means that 30 per cent of the heat in the gasoline was lost. With proper combustion in the engine and correct carburetor adjustment, 20 to 30 per cent greater mileage should have been secured per gallon of gasoline used. One of the cars showed 13.2 per cent carbon monoxide, which corresponds to a loss of 50 per cent of the gasoline used — truly an enormous and unnecessary wastage of gasoline.

Hydrogen and methane:—The hydrogen and methane in exhaust gases are due to the decomposition of the gasoline in the absence of oxygen, and perhaps in a lesser degree to reactions in which water vapor takes part. In a general way the hydrogen increases proportionally with the carbon monoxide. The methane percentage is very low when the engine is running under the best conditions.

Gasoline vapor:— The gasoline vapor in exhaust gases is due to poor ignition, poor mixing and vaporization of the gasoline and air, too rich mixtures, or incomplete flame propagation. One or several of the above conditions may cause small portions of the gasoline to pass through the engine without reacting with the oxygen present in the air.

In the analyses given in this report, the gasoline vapor and all other hydrocarbons appear as methane. In other words, the analysis gives the equivalent methane value for all the hydrocarbons in the exhaust gas, and the result is correct as regards carbon content for computing the total volume of exhaust gases from the gasoline consumption and the carbon content of the gasoline. The determination of gasoline vapor as methane causes the hydrogen value in the analysis to be somewhat less than its true value. This error in the hydrogen value has no effect on calculation of the true volume of carbon monoxide, carbon dioxide and methane equivalent of hydrocarbons produced in the tests.

Finally it must be recognized that absolutely all the gasoline fed into the engine does not appear in the exhaust gas analysis. In cylinders with poorly fitting piston rings and in very cold weather some gasoline escapes into the crank case, also traces of carbon remain behind on the cylinder walls. To partly compensate for this loss some constituents of the exhaust gas undoubtedly came from the cracking of lubricating oil in the cylinders.

* Hood, O. P. and Kudlich, R. H., and Burrell, G. A., Gasoline Mine Locomotives in Relation to Safety and Health: Bureau of Mines, Bulletin 74, 1915, pp. 69-71.

Unsaturated hydrocarbons:—Unsaturated hydrocarbons occur at times in exhaust gases, especially when the carburetor has a very rich adjustment. The exhaust gases were tested from time to time for unsaturated hydrocarbons on a special Orsat gas apparatus. The amount present usually was not more than .1 per cent, the experimental error of analysis. In exceptional cases where a very rich mixture was used and the car in poor adjustment, the percentage of unsaturated hydrocarbons was as high as 1 per cent. In order to keep the exhaust gas calculation correct, the unsaturated hydrocarbons value was doubled and reported as methane.

METHOD OF MEASURING GASOLINE CONSUMED

In order that the gasoline consumption could be measured accurately under test conditions, t was necessary to equip the cars used with a special gasoline measuring device. After the exhaust sampling pipe was installed, the gasoline measuring apparatus, Figure 7, was put in position and connected to the carburetor which was disconnected from its usual gasoline supply.

This apparatus, Figure 7, consists of a five gallon can "v," equipped with pressure gauge "a," can containing gasoline of the brand used by car when it was received for test. Gasoline was forced from "v" to manifold "b" through one-quarter inch I.D. copper tubing "c," union "d," and gasoline stopcock "e," by means of air supplied through flexible tubing "f," and automobile inner tube valve "g," by pump, operated by party taking gas samples on test. On tests of pleasure cars the gasoline supply tank and pump were placed in back seat, and on trucks in truck body, "i" is a twelve inch by twelve inch by one inch cast iron block on which the apparatus is mounted and on test is placed on front seat floor boards. This cast iron block is drilled and tapped for three leveling screws, "j," two in front and one in the back of the apparatus for leveling when taking readings, noted by level "k". The tube, "l," consists of brass and varies in size as follows:—

One and one-half inches diameter by twenty-three inches long 500 c.c. capacity, gasoline measured to 1 c.c. for five-passenger cars and light speed trucks.

Two inches diameter by twenty-three inches long 950 c.c. capacity, gasoline measured to 2 c.c. for seven passenger cars and light trucks.

Three inches diameter by twenty-three inches long 1950 c.c. capacity, gasoline measured to 2 c.c. for use on heavier trucks of large capacity.

Four inches diameter by twenty-three inches long 3800 c.c. capacity, gasoline measured to 5 c.c. used on loaded heavy truck when excessive gasoline consumption was indicated on light load tests.

These tubes were mounted on board "m," and connected to manifold "b," by union "n," through gasoline stopcock "q," and were fitted with gauge glass "p," for indicating gasoline level in tube for which the corresponding capacities could be noted on gauge "c". A thermometer "r," was secured to tube "e," for noting temperature of gasoline, the bulb of the thermometer and portion of the scale not used were protected from air by insulating material. Gasoline was supplied to carburetor from manifold "b" through gasoline stopcock "s," union "t" and one-half inch to one-quarter inch I.D. tubing "u," depending upon size of car or truck connected to carburetor by a suitable union.

The apparatus as installed ready for use on test is shown by Plate 3 and the operation is as follows:—

Air is pumped into can "v" to about two pounds per square inch pressure. Gasoline is forced through connections to manifold "b," to carburetor and with gasoline stopcock "q," open into tube "l". On road tests with apparatus level tube, "l," is filled to zero mark of scale, when stopcock "q" is quickly closed. Gasoline stopcocks "e" and "s" are open and when motor is running and no test data taken, it is supplied with gasoline direct from supply "v". On tests with car standing and apparatus level the measuring tube was filled above the zero mark and motor

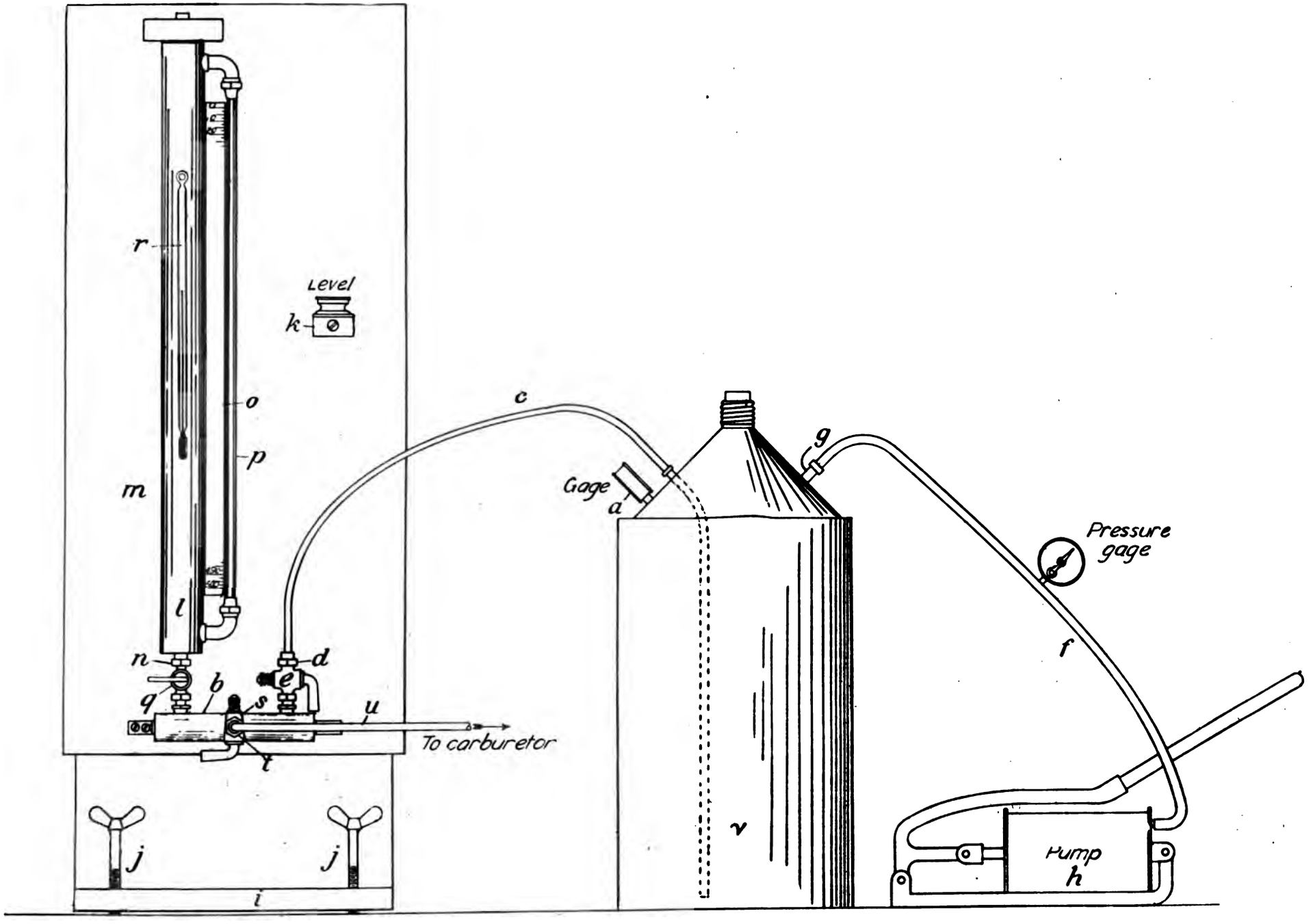

r
Level
k
o
p
m
l
n
q
b
d
e
s
u
t
c
Gage
a
g
Pressure
gage
f
To carburetor
v
Pump
h
j
j
i

Figure 7

allowed to run on gasoline from measuring tube. The stop watch and test started when gasoline level reached zero level of measuring tube. At finish of test, exactly on time of stopping stop-watch recording test time, gasoline stopcock "q" is closed and "e" opened, again supplying motor from reserve supply.

With apparatus level, the gasoline consumption in c.c. for test road on scale "o". Tube "1" is again filled by opening cock "q" and closing same when zero mark on scale is passed.

For road test gasoline measurement the operation is similar only in that the measuring tube is filled to zero level and cock "e" is closed and stop-watch started coincident with signal given when passing starting point of course, after which cock "q" is opened. Coincident with signal given when finish mark of course is passed, stop-watch is stopped, cock "q" closed and cock "e" opened. All test readings are recorded with apparatus level and with car standing, which condition is maintained while tube "1" is filled to zero mark preparatory for next test.

METHOD OF COMPUTING RESULTS

Volume of exhaust gases:—The total volume of exhaust gases produced per gallon of gasoline consumed was computed from the analysis of the exhaust gases and the weight and analysis of the gasoline. This computation is based on the assumption that all the carbon in the gasoline appears in the exhaust gases. As a matter of fact, there is a small error due to solid particles of carbon in the exhaust and on the motor surfaces and leakage of gasoline into the crank case. This error may be partly compensated or exceeded in some cases by lubricating oil burning in the cylinders. The total error is probably negligible. Some tests were made with the engine idling in which the exhaust gases were collected and measured in a fifty cubic foot calibrated gas tank. The measured volumes checked to within 6 per cent of the volumes computed from the analysis in the usual manner.

The volume of exhaust gases was computed by the following method:

From Gasoline Analysis:

a = Sp. Gr. of gasoline at 63° F.
b = Per cent carbon in gasoline.
8.33 = Weight one gallon water, in pounds, at 60° F.
8.33ab = Pounds carbon in one gallon gasoline, (1)

From Gas Analysis:

c = Per cent CO_2 in exhaust, by volume.
d = Per cent CO in exhaust, by volume.
e = Per cent Ch_4 in exhaust, by volume.

0.1158 = Weight in lbs. 1 Cu. Ft. CO_2, 65° F. and 29.92" Hg.
.0732 = Weight in lbs. 1 Cu. Ft. CO, 65° F. and 29.92" Hg.
.0420 = Weight in lbs. 1 Cu. Ft. CH_4, 65° F. and 29.92" Hg.
.1158 x 3/11[a] = 0.316 = lbs. Carbon in 1 Cu. Ft. CO_2 at 65° F., 29.92" Hg.
.0732 x 3/7[a] = .0314 = lbs. Carbon in 1 Cu. Ft. CO at 65° F., 29.92" Hg.
.0420 x 3/4[a] = .0315 = lbs. Carbon in 1 Cu. Ft. CH_4 at 65° F., 29.92" Hg.
0.0316c+0.0314d+0.0315e = Total Lbs. Carbon in 1 Cu. Ft. exhaust gas.
This expression may be simplified by using the mean value 0.0315 as follows:
0.0315 (c+d+e) = Total Lbs. Carbon in 1 Cu. Ft. Exhaust Gases (2) Dividing (1) by (2)

$$\frac{8.33ab}{0.0315(c+d+e)} = \frac{264.4ab}{c+d+e}$$ = Cu. Ft. Exhaust gas at 65° F., 29.92" Hg. per gallon of gasoline.

The numerator of the above expression is constant for each gasoline and represents the total cubic feet of carbon containing gases (CO_2, CO and CH_4) that is produced by gasoline of the given

[a] Ratio of atomic weight of carbon to molecular weight of gas.

PLATE 3. TEST APPARATUS INSTALLED ON TRUCK READY FOR TEST

specific gravity and carbon content. The denominator varies with each test and represents the proportion by volume or carbon containing gases in one cubic foot of exhaust gas.

ANALYSES OF GASOLINE USED

All cars were tested with the same brand of gasoline as was being used in the car at the time it was submitted for test. In order to avoid analyzing a large number of samples of the same brand, a large stock of each of the brands in use around Pittsburgh was obtained and carefully sampled; complete analyses of each sample are given in Table 7. The ultimate analyses, giving carbon and hydrogen content were made by W. A. Selvig, Analytical Chemist, and the standard distillation tests and specific gravity determinations were made in the Bureau's petroleum laboratory under the direction of E. W. Dean, Petroleum Chemist.

TABLE NO. 7

ANALYSES OF GASOLINE USED ON TESTS

KIND	Sample Number	Gravity at 60° F.	Degrees Baume 60° F.	Per cent Unsaturation	DISTILLATION IN 100 CC. ENGLER FLASK, TEMPERATURE °F.						ULTIMATE ANALYSIS	
					First Drop	PER CENT			Dry Point	Average	Per cent Carbon	Per cent Hydrogen
						20	50	90				
A.....	1	0.713	66.4	2.5	88	151	225	381	441	239	84.3	15.7
A.....	9	0.710	67.2	.....	84	149	234	385	421	241	84.4	15.4
AM.....	2	0.731	51.5	.....	93	181	266	394	451	282	84.3	15.7
AM.....	3	0.743	59.2	1.5	95	192	271	405	457	275	84.5	14.5
AM.....	10	0.748	57.2	.....	86	219	277	392	435	278	84.5	15.2
G.....	4	0.730	61.8	2.0	104	187	259	363	414	259	85.2	14.8
G.....	8	0.736	60.2	.....	115	194	241	352	419	253	85.1	14.7
G.....	11	0.747	57.4	2.0	122	219	262	374	433	275	84.9	15.3
M.....	5	0.722	63.9	3.0	84	167	284	432	448	277	85.3	14.7
MM.....	6	0.742	58.7	2.5	80	201	302	432	448	289	86.0	14.0
B.....	7	0.796	45.9	2.0	115	199	248	381	430	264	88.3	11.7

COMPARISON OF QUALITY OF GASOLINE USED IN PITTSBURGH TESTS WITH THAT SOLD IN NEW YORK CITY AND BROOKLYN

Since the quality of gasoline may affect the proportion of carbon monoxide produced, the question has properly been raised as to whether the gasoline used in the Pittsburgh district is the same as commonly used in New York. To answer this, a survey was made by the Petroleum Division of the Bureau of the gasolines sold in New York City and Brooklyn during the month of January, 1920. The analyses of ten representative samples of various brands of gasoline collected in this survey are given in Table 8. A comparison of the average analyses of Pittsburgh and New York gasolines is given in Table 9.

TABLE 8

ANALYSES OF GASOLINES SOLD IN NEW YORK AND BROOKLYN, N. Y., IN MONTH OF JANUARY, 1920

SAMPLE NUMBER	Gravity at 60° F.	Degrees Baume at 60° F.	Per cent Unsaturation	DISTILLATION IN 100 CC. ENGLER FLASK, TEMPERATURE °F.					
				First Drop	PER CENT			Dry Point	Average
					20	50	90		
1	0.737	60.0	8.0	106	181	253	343	388	252
2	0.743	58.4	3.0	127	216	264	354	419	268
3	0.753	55.9	14.0	151	212	268	356	430	271
4	0.738	59.7	8.0	118	201	255	343	399	257
5	0.732	61.3	2.0	140	201	246	367	427	266
6	0.745	57.9	4.0	124	216	266	379	426	271
7	0.735	60.5	8.0	111	203	257	356	403	261
8	0.741	58.9	6.0	111	198	246	347	397	252
9	0.730	61.8	4.0	124	198	234	325	412	246
10	0.755	55.4	2.0	122	212	266	363	430	270
Average	0.741	58.9	5.9	121	204	256	354	413	261

TABLE 9

COMPARISON OF AVERAGE ANALYSES OF GASOLINE USED IN NEW YORK AND PITTSBURGH

LOCATION	Number of Analyses	Sp. Gr.	Baume	DISTILLATION DEGREES F.		
				First Drop	Dry Point	Average
New York and Brooklyn	10	0.741	58.9	121	413	261
Pittsburgh	6	0.730	61.9	92	443	270

It will be noted from the two tables that the average distillation temperature of the Pittsburgh samples is nine degrees higher than the average temperature of the New York gasolines, although the Pittsburgh samples start to distill at a considerably lower temperature. In other words, the Pittsburgh gasolines have a larger range of distillation and probably consist of a blend of volatile casing head gasoline with a less volatile gasoline than is marketed in New York. Such gasoline has the property of starting a cold motor easily, due to the low initial distillation temperature, but on account of the high dry point, it would be equally or more difficult to secure proper vaporization for complete combustion in the cylinder, than would be the case with the New York gasolines.

TABLE 10

CLASS 1

Average gasoline consumption, exhaust gas analyses and quantity of carbon monoxide for 5-passenger cars tested under winter and summer conditions. Average load tests.

TEST CONDITION	GASOLINE USED PER HOUR AT 60° F. GALLONS			CARBON DIOXIDE (CO_2)			OXYGEN (O_2)			CARBON MONOXIDE (CO)			METHANE (CH_4)			HYDROGEN (H_2)			NITROGEN (N_2)			CARBON MONOXIDE PER HOUR, CUBIC FEET AT 65° F., 29.92" Hg.		
Averages of	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A
Car standing, engine racing*	.86	1.123	.942	9.1	7.8	8.7	1.5	3.1	1.9	6.9	7.1	7.0	.8	2.1	1.2	3.0	2.9	3.0	78.8	77.0	78.2	55.6	76.9	62.3
Car standing, engine idling*	.420	.523	.452	8.9	6.7	8.3	1.4	4.3	2.2	7.6	7.3	7.5	.6	2.5	1.1	3.7	3.1	3.5	77.8	76.1	77.4	30.8	39.2	33.4
Running 15 M. P. H. down 3 % grade	.650	.552	.606	9.5	7.5	8.7	1.4	4.0	2.5	6.5	6.6	6.5	.9	2.0	1.3	2.9	2.6	2.8	78.8	77.3	78.2	42.7	38.4	41.4
Running 10 M. P H. down 3 % grade	.500	.410	.463	8.6	7.3	8.1	1.4	4.6	2.7	7.0	6.2	6.7	.7	2.4	1.4	3.1	2.5	2.8	79.2	77.0	78.2	35.7	27.4	32.4
Running 3 M. P. H. down 3 % grade	.460	.....	.460	9.5	.....	9.5	1.5	.....	1.5	6.0	.....	6.0	.7	.....	.7	2.7	.....	2.7	79.6	.....	79.6	28.8	.....	28.8
Accelerating from rest to 15 M. P. H.	1.200	.....	1.200	10.0	.....	10.0	1.6	.....	1.6	5.8	.....	5.8	.8	.....	.8	2.4	.....	2.4	79.4	.....	79.4	71.4	.....	71.4
Running 15 M. P. H. up 3 % grade	1.233	1.247	1.240	10.2	9.9	10.1	1.1	.5	.9	5.7	6.7	6.1	.6	.7	.6	2.6	3.1	2.8	79.8	79.1	79.5	72.2	82.9	77.0
Running 10 M. P. H. up 3 % grade	.890	.841	.870	9.9	9.8	9.8	1.5	.6	1.1	5.7	6.9	6.2	.5	.6	.5	2.6	3.3	2.9	79.8	78.8	79.5	52.6	57.5	54.8
Running 3 M. P. H. up 3 % grade	.660	.....	.660	9.8	.....	9.8	.9	.....	.9	6.5	.....	6.5	.6	.....	.6	3.0	.....	3.0	79.2	.....	79.2	41.8	.....	41.8
Accelerating from rest to 15 M. P. H., level	1.180	.....	1.180	9.9	.....	9.9	1.5	.....	1.5	5.6	.....	5.6	.9	.....	.9	2.2	.....	2.2	79.9	.....	79.9	72.9	.....	72.9
Running 20 M. P. H., level	.....	1.118	1.118	.....	9.6	9.6	.....	1.2	1.2	....	6.5	6.5	.....	.9	.9	.....	3.0	3.0	.....	78.8	78.8	.....	72.8	72.8
Running 15 M. P. H., level	.960	.819	.897	9.3	9.5	9.4	2.2	.9	1.7	5.6	6.8	6.1	.8	.9	.8	2.8	3.0	2.9	79.3	78.9	79.1	63.0	57.9	60.7
Running 10 M. P. H., level	.660	.579	.624	9.3	8.4	8.9	1.9	1.6	1.8	6.3	7.8	6.9	.6	1.1	.8	3.1	3.7	3.3	78.8	77.4	78.3	46.9	44.1	45.8
Running 3 M. P. H., level	.530	.....	.530	9.1	.....	9.1	1.6	.....	1.6	6.7	.....	6.7	.6	....	.6	3.0	.....	3.0	79.0	.....	79.0	36.3	.....	36.3

W — 11 cars tested under winter conditions.
S — 9 cars tested under summer conditions.
A — All tests.
* Results, averages of tests made on 5 cars under summer conditions, all cars tested under winter conditions.

TABLE 11

CLASS 2

Average gasoline consumption, exhaust gas analyses and quantity of carbon monoxide for 7-passenger cars tested under winter and summer conditions. Average of light and full load tests.

TEST CONDITION	GASOLINE USED PER HOUR AT 60° F. GALLONS			CARBON DIOXIDE (CO_2)			OXYGEN (O_2)			CARBON MONOXIDE (CO)			METHANE (CH_4)			HYDROGEN (H_2)			NITROGEN (N_2)			CARBON MONOXIDE PER HOUR, CUBIC FEET AT 65° F., 29.92" Hg.		
Averages of	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A
Car standing, engine racing*	1.690	1.030	1.608	7.3	9.4	7.6	3.5	1.2	3.2	7.8	6.7	7.7	1.4	.7	1.3	2.9	2.8	2.9	77.1	79.2	77.3	137.0	67.5	105.0
Car standing, engine idling*	.520	.285	.491	8.0	7.7	8.0	4.3	3.9	4.3	6.3	5.7	6.2	1.2	1.6	1.3	2.0	1.7	2.0	78.2	79.4	78.2	35.3	17.8	33.1
Running 15 M. P. H. down 3% grade	.885	.978	.928	6.8	6.2	6.5	5.3	5.5	5.4	7.0	6.9	7.0	1.5	3.0	2.2	2.8	2.0	2.3	76.6	76.4	76.6	68.2	70.0	69.2
Running 10 M. P. H. down 3% grade	.540	.694	.611	7.2	6.3	6.8	5.4	5.8	5.6	5.7	6.4	6.0	1.0	3.0	2.0	1.9	1.8	2.0	78.8	76.7	77.6	35.4	49.2	41.8
Running 3 M. P. H. down 3% grade	.590	.....	.590	6.7	.....	6.7	5.3	.....	5.3	6.4	.....	6.4	1.3	.....	1.3	2.8	.....	2.8	77.5	.....	77.5	44.4	.....	44.4
Accelerating from rest to 15 M. P. H. up 3% grade	2.176	.....	2.176	8.9	.....	8.9	2.6	.....	2.6	6.4	.....	6.4	1.1	.....	1.1	2.5	.....	2.5	78.5	.....	78.5	144.0	.....	144.0
Running 15 M. P. H. up 3% grade	1.920	1.913	1.916	8.7	8.7	8.7	1.8	.7	1.3	7.8	8.3	8.0	.7	1.0	.8	2.5	3.9	3.1	77.5	77.4	77.5	136.0	147.0	141.2
Running 10 M. P. H. up 3% grade	1.350	1.359	1.355	8.6	8.3	8.5	2.0	.7	1.4	6.7	9.0	7.8	.9	1.2	1.0	3.2	4.1	3.6	78.6	76.4	77.7	90.9	110.3	100.0
Running 3 M. P. H. up 3% grade	.961	.....	.961	7.3	.....	7.3	3.2	.....	3.2	8.8	.....	8.8	1.3	.....	1.3	3.9	.....	3.9	75.5	.....	75.5	81.5	.....	81.5
Accelerating from rest to 15 M. P. H., level	1.850	.....	1.850	8.9	.....	8.9	3.0	.....	3.0	6.0	.....	6.0	.9	.....	.9	2.3	.....	2.3	78.9	.....	78.9	120.1	.....	120.1
Running 20 M. P. H., level	.....	1.763	1.763	.....	8.2	8.2	.....	1.3	1.3	.....	8.4	8.4	.....	1.4	1.4	.....	3.7	3.7	.....	77.1	77.1	.....	137.0	137.0
Running 15 M. P. H., level	1.400	1.410	1.405	8.4	8.0	8.2	2.5	1.5	2.0	7.2	8.6	7.9	1.0	1.4	1.2	3.2	3.8	3.5	77.7	76.6	77.2	98.9	111.8	104.8
Running 10 M. P. H., level	.970	9.64	.968	8.3	8.0	8.2	2.8	1.5	2.2	6.5	8.3	7.4	.9	1.6	1.2	2.9	3.6	3.2	78.6	77.0	77.8	68.0	75.5	71.4
Running 3 M. P. H., level	.750	.....	.750	8.0	.....	8.0	3.4	.....	3.4	6.6	.....	6.6	1.2	.....	1.2	2.8	.....	2.8	78.0	.....	78.0	53.1	.....	53.1

W — Seven 7-passenger cars under winter conditions.
S — Six 7-passenger cars under summer conditions.
A — All tests.
* Only one car tested under summer conditions.

TABLE 12

CLASS 3

Average gasoline consumption, exhaust gas analyses, and quantity of carbon monoxide for trucks up to 1½ tons capacity tested under winter and summer conditions.

Average light and full loads.

TEST CONDITION	GASOLINE USED PER HOUR AT 60° F. GALLONS			CARBON DIOXIDE (CO_2)			OXYGEN (O_2)			CARBON MONOXIDE (CO)			METHANE (CH_4)			HYDROGEN (H_2)			NITROGEN (N_2)			CARBON MONOXIDE PER HOUR, CUBIC FEET AT 65° F., 29.92" Hg.		
Averages of	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A
Car standing, engine racing	.940	.....	.940	8.3	.....	8.3	2.0	.....	2.0	7.7	.....	7.7	1.2	.....	1.2	4.0	.....	4.0	76.8	.....	76.8	67.9	.....	67.9
Car standing, engine idling	.440	.....	.440	6.6	.....	6.6	4.2	.....	4.2	7.1	.....	7.1	2.1	.....	2.1	3.7	.....	3.7	76.3	.....	76.3	31.0	.....	31.0
Running 15 M. P. H. down 3 % grade	.730	.658	.688	7.3	6.7	7.0	3.7	5.6	4.8	6.7	6.3	6.5	1.6	1.8	1.7	3.2	2.0	2.5	77.5	77.6	77.5	50.1	47.4	48.5
Running 10 M. P. H. down 3 % grade	.640	.498	.557	6.8	7.2	7.0	4.1	5.5	5.0	7.2	5.7	6.3	2.2	1.6	2.0	3.4	1.8	2.5	76.3	78.0	77.2	46.0	33.8	38.8
Running 3 M. P. H. down 3 % grade	.500	.....	.500	6.9	.....	6.9	3.5	.....	3.5	7.7	.....	7.7	1.9	.....	1.9	3.5	.....	3.5	76.5	.....	76.5	37.2	.....	37.2
Accelerating from rest to 15 M. P. H. up 3 % grade	1.200	.....	1.200	9.6	.....	9.6	2.5	.....	2.5	5.4	.....	5.4	1.0	.....	1.0	2.2	.....	2.2	79.3	.....	79.3	65.1	.....	65.1
Running 15 M. P. H. up 3 % grade	1.420	1.618	1.535	9.7	9.7	9.7	1.3	1.1	1.2	6.1	6.3	6.2	.6	.7	.7	2.9	3.0	2.9	79.4	79.2	79.3	83.2	104.5	95.6
Running 10 M. P. H. up 3 % grade	1.110	1.117	1.114	9.3	9.3	9.3	1.5	.8	1.1	6.4	7.4	7.0	.9	.8	.8	3.3	3.4	3.4	78.6	78.3	78.4	66.3	79.9	74.3
Running 3 M. P. H. up 3 % grade	.650	.....	.650	7.8	.....	7.8	1.8	.....	1.8	9.0	.....	9.0	1.0	.....	1.0	4.4	.....	4.4	76.0	.....	76.0	54.9	.....	54.9
Accelerating from rest to 15 M. P. H., level	1.050	.....	1.050	9.5	.....	9.5	2.9	.....	2.9	4.8	.....	4.8	1.0	.....	1.0	2.2	.....	2.2	79.6	.....	79.6	60.4	.....	60.4
Running 20 M. P. H., level	.....	1.354	1.354	.....	9.2	9.2	.....	1.2	1.2	.....	7.0	7.0	.....	.7	.7	.....	3.2	3.2	.....	78.7	78.7	.....	94.0	94.0
Running 15 M. P. H., level	.990	1.150	1.083	9.0	9.0	9.0	1.8	1.7	1.8	6.7	6.7	6.7	1.0	1.1	1.1	3.4	2.7	2.9	78.1	78.8	78.5	63.7	77.2	71.7
Running 10 M. P. H., level	.850	.783	.811	8.3	8.5	8.4	2.0	1.5	1.7	7.9	7.6	7.7	1.1	1.2	1.2	3.2	3.5	3.4	77.5	77.7	77.6	61.1	58.7	59.8
Running 3 M. P. H., level	.620	.....	.620	7.5	.....	7.5	2.6	.....	2.6	7.8	.....	7.8	1.4	.....	1.4	3.9	.....	3.9	76.8	.....	76.8	47.4	.....	47.4

W — 5 trucks tested under winter conditions.
S — 7 trucks tested under summer conditions.
A — All tests.

TABLE 13

CLASS 4

Average gasoline consumption, exhaust gas analyses, and quantity of carbon monoxide for trucks one one-half to three tons, inclusive, capacity: tested under summer conditions. Average of light and full load tests

TEST CONDITION	Gasoline per hour, gallons at 60° F.	EXHAUST GAS ANALYSES, PER CENT BY VOLUME						Carbon monoxide per hour cu. ft. at 65° F. 29.92" Hg.
		Carbon dioxide (CO_2)	Oxygen (O_2)	Carbon monoxide (CO)	Methane (CH_4)	Hydrogen (H_2)	Nitrogen (N_2)	
Car standing, engine racing*.....	1.281	10.5	1.5	4.7	1.2	1.3	80.8	55.8
Car standing, engine idling*.....	.436	8.5	6.7	2.4	1.1	.7	80.6	13.2
Running 15 M. P. H. down 3% grade†.....	1.079	6.6	5.4	6.6	2.0	1.9	77.5	77.8
Running 10 M. P. H. down 3% grade	.854	6.9	5.2	6.4	2.0	1.8	77.7	59.5
Running 6 M. P. H. down 3% grade.	.501	6.9	7.3	4.0	1.5	1.2	79.1	28.9
Running 15 M. P. H. up 3% grade†.	2.423	10.2	.8	5.5	.8	2.2	80.5	133.5
Running 10 M. P. H. up 3% grade..	2.069	9.6	.8	6.9	.8	3.0	78.9	134.7
Running 6 M. P. H. up 3% grade...	1.438	9.3	1.0	7.1	.8	3.3	78.5	99.7
Running 15 M. P. H. on level grade†.	1.694	9.3	1.5	6.2	1.1	2.2	79.7	103.9
Running 10 M. P. H. on level grade.	1.399	8.4	1.6	7.5	1.0	3.2	78.3	104.0
Running 6 M. P. H. on level grade..	.924	8.6	1.8	7.3	1.0	3.2	78.1	67.6

Results unless otherwise noted, averages of tests on 22 trucks.
* Results, averages of tests on 4 trucks under these conditions.
† Results, averages of tests on 15 trucks under these conditions.

TABLE 14

CLASS 5

Average gasoline consumption, exhaust gas analyses, and quantity of carbon monoxide for trucks three and one-half to four and one-half tons, inclusive, capacity: tested under summer conditions. Average of light and full load tests

TEST CONDITION	Gasoline per hour, gallons at 60° F.	EXHAUST GAS ANALYSES, PER CENT BY VOLUME						Carbon monoxide per hour cu. ft. at 65° F. 29.92" Hg.
		Carbon dioxide (CO_2)	Oxygen (O_2)	Carbon monoxide (CO)	Methane (CH_4)	Hydrogen (H_2)	Nitrogen (N_2)	
Car standing, engine racing*.....	1.982	7.7	2.0	8.6	1.5	3.7	76.5	158.2
Car standing, engine idling*.....	.810	5.8	4.3	8.8	2.9	3.4	74.8	66.4
Running 15 M. P. H. down 3% grade†.....	1.764	8.8	2.7	5.7	1.2	1.9	79.7	109.0
Running 10 M. P. H. down 3% grade	1.338	7.8	3.2	7.1	1.5	2.6	77.8	97.8
Running 6 M. P. H. down 3% grade.	.776	6.8	5.4	6.2	1.7	2.1	70.8	55.0
Running 15 M. P. H. up 3% grade†.	3.747	10.8	.5	4.7	.7	1.7	81.6	183.9
Running 10 M. P. H. up 3% grade..	3.049	10.1	.6	6.3	.6	2.8	79.6	138.1
Running 6 M. P. H. up 3% grade...	1.880	9.5	.6	7.4	.6	3.5	78.4	132.6
Running 15 M. P. H. on level grade†.	2.624	10.4	1.1	4.8	.7	1.7	81.3	131.2
Running 10 M. P. H. on level grade..	2.015	8.8	1.1	7.5	.9	3.2	78.5	147.6
Running 6 M. P. H. on level grade..	1.270	8.8	1.1	7.8	.9	3.3	78.1	92.6

Results unless otherwise noted, averages of tests on 16 trucks.
* Results, averages of tests on 3 trucks under this condition.
† Results, averages of tests on 5 trucks under these conditions.

TABLE 15

CLASS 6

Average gasoline consumption, exhaust gas analyses, and quantity of carbon monoxide for trucks five ton and over capacity; tested under summer conditions. Average of light and full load tests.

TEST CONDITION	Gasoline per hour, gallons at 60° F.	EXHAUST GAS ANALYSES, PER CENT BY VOLUME						Carbon monoxide per hour cu. ft. at 65° F. 29.92″ Hg.
		Carbon dioxide (CO_2)	Oxygen (O_2)	Carbon monoxide (CO)	Methane (CH_4)	Hydrogen (H_2)	Nitrogen (N_2)	
Car standing, engine racing*.....	1.412	8.7	1.7	7.5	1.2	3.4	77.5	105.2
Car standing, engine idling*.....	.730	7.1	4.6	6.8	1.9	2.6	77.0	50.5
Running 10 M. P. H. down 3% grade	1.336	7.1	5.2	5.9	1.9	1.8	78.1	90.0
Running 6 M. P. H. down 3% grade.	.824	6.9	5.9	5.7	2.3	1.5	77.7	54.5
Running 10 M. P. H. up 3% grade..	3.471	10.8	.5	5.1	.7	2.0	80.9	181.6
Running 6 M. P. H. up 3% grade...	2.301	9.6	.6	6.8	.7	3.2	79.1	148.3
Running 10 M. P. H. on level grade.	2.243	8.9	1.4	6.9	1.1	2.8	78.9	151.6
Running 6 M. P. H. on level grade..	1.481	8.5	1.7	7.5	1.1	3.3	77.9	110.3

Results unless otherwise noted, averages of tests on 18 trucks.

* Results, averages of tests on 6 trucks under these conditions.

TABLE 16

CLASS 2

Average gasoline consumption, exhaust gas analyses and quantity of carbon monoxide for 7-passenger cars tested under winter and summer conditions.
Results of full load tests.
Exhaust gas analyses per cent (by volume).

TEST CONDITION	GASOLINE USED PER HOUR AT 60° F. GALLONS			CARBON DIOXIDE (CO_2)			OXYGEN (O_2)			CARBON MONOXIDE (CO)			METHANE (CH_4)			HYDROGEN (H_2)			NITROGEN (N_2)			CARBON MONOXIDE PER HOUR, CUBIC FEET AT 65° F. 29.92" Hg.		
Averages of	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A
Running 15 M. P. H. down 3 % grade.	.840	1.030	.928	7.1	5.8	6.5	4.5	6.0	5.2	7.2	7.1	7.2	1.4	3.3	2.3	3.1	1.9	2.5	76.7	75.9	76.3	64.3	75.8	69.6
Running 10 M. P. H. down 3 % grade.	.510	.671	.595	7.5	5.7	6.7	5.7	7.1	6.4	5.1	5.8	5.7	.8	3.7	1.9	1.6	1.3	1.4	79.3	76.4	77.9	32.1	44.8	38.0
Running 3 M. P. H. down 3 % grade..	.530	.....	.660	6.4	.....	6.4	5.7	.....	5.7	6.6	.....	6.6	1.3	.....	1.3	3.1	.....	3.1	76.9	.....	76.9	50.3	.....	50.3
Accelerating from rest to 15 M. P. H. up 3 % grade.....	2.350	.....	2.350	8.7	.....	8.7	2.9	.....	2.9	6.5	.....	6.5	1.1	.....	1.1	2.6	.....	2.6	78.2	.....	78.2	163.6	.....	163.6
Running 15 M. P. H. up 3 % grade....	1.960	1.903	1.934	8.9	8.7	8.8	1.7	.7	1.2	8.1	8.3	8.2	.5	.9	.7	3.7	4.0	3.8	77.1	77.4	77.3	150.4	146.7	148.5
Running 10 M. P. H. up 3 % grade....	1.370	1.440	1.402	9.0	8.3	8.7	2.0	.8	1.4	6.0	8.9	7.3	1.0	1.1	1.0	2.8	4.3	3.5	79.2	76.6	78.1	86.0	117.2	100.4
Running 3 M. P. H. up 3 % grade.....	1.040	.....	1.040	7.0	.....	7.0	3.1	.....	3.1	8.4	.....	8.4	1.3	.....	1.3	4.1	.....	4.1	76.1	.....	76.1	88.5	.....	88.5
Accelerating from rest to 15 M. P. H. level.....	1.940	.....	1.940	8.9	.....	8.9	2.9	.....	2.9	6.4	.....	6.4	.8	.....	.8	2.6	.....	2.6	78.4	.....	78.4	137.2	.....	137.2
Running 20 M. P. H. on level grade...	.....	1.774	1.774	.....	8.3	8.3	.....	1.1	1.1	.....	8.5	8.5	.....	1.2	1.2	.....	3.9	3.9	.....	77.0	77.0	.....	140.2	140.2
Running 15 M. P. H. on level grade...	1.540	1.457	1.501	8.5	7.9	8.2	2.2	1.5	1.9	7.8	8.6	8.2	1.1	1.5	1.3	3.6	3.9	3.7	76.8	76.6	76.7	110.4	115.6	112.8
Running 10 M. P. H. on level grade...	1.010	.985	.998	8.6	8.0	8.3	2.5	1.5	2.0	6.6	8.2	7.3	.7	1.6	1.1	2.9	3.7	3.3	78.7	77.0	78.0	71.0	76.6	73.6
Running 3 M. P. H. on level grade....	.740	.....	.740	8.0	.....	8.0	3.7	.....	3.7	6.2	.....	6.2	1.4	.....	1.4	2.6	.....	2.6	78.1	.....	78.1	51.9	.....	51.9

W — Seven cars tested under winter conditions.
S — Six cars tested under summer conditions.
A — All tests.

TABLE 17

CLASS 3

Average gasoline consumption, exhaust gas analyses and quantity of carbon monoxide for trucks up to 1½ tons capacity, tested under winter and summer conditions.

Results of full load tests.

TEST CONDITION	GASOLINE USED PER HOUR AT 60° F. GALLONS			CARBON DIOXIDE (CO_2)			OXYGEN (O_2)			CARBON MONOXIDE (CO)			METHANE (CH_4)			HYDROGEN (H_2)			NITROGEN (N_2)			CARBON MONOXIDE PER HOUR, AT 65° F., CUBIC FEET 29.92" Hg.		
Averages of	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A	W	S	A
Running 15 M. P. H. down 3 % grade	.760	.646	.694	7.0	6.1	6.5	4.4	7.4	6.2	6.4	5.4	5.8	1.7	1.8	1.8	2.9	1.6	2.1	77.6	77.7	77.6	51.6	45.6	48.1
Running 10 M. P. H. down 3 % grade	.590	.501	.538	7.2	6.9	7.0	4.2	5.9	5.2	6.7	5.9	6.2	2.2	1.8	2.0	3.2	1.9	2.4	76.5	77.6	77.2	39.9	35.0	37.0
Running 3 M. P. H. down 3 % grade	.560	.....	.560	7.2	.....	7.2	3.4	.....	3.4	7.9	.....	7.9	1.6	.....	1.6	3.5	.....	3.5	76.4	.....	76.4	43.1	.....	43.1
Accelerating from rest to 15 M. P. H. up 3 % grade	1.200	.....	1.200	9.6	.....	9.6	2.7	.....	2.7	5.4	.....	5.4	.8	.....	.8	1.9	.....	1.9	79.6	.....	79.6	65.9	.....	65.9
Running 15 M. P. H. up 3 % grade	1.600	1.858	1.750	9.8	9.3	9.5	1.1	.6	.8	6.0	7.5	6.9	.6	.7	.7	2.7	3.0	3.2	79.8	78.3	78.9	80.0	138.3	117.7
Running 10 M. P. H. up 3 % grade	1.220	1.212	1.218	9.6	9.5	9.5	1.6	.6	1.0	5.7	7.3	6.6	.6	.8	.7	2.6	3.5	3.1	79.9	78.3	79.1	68.5	86.3	78.9
Running 3 M. P. H. up 3 % grade	.720	.....	.720	7.4	.....	7.4	2.1	.....	2.1	9.5	.....	9.5	.8	.....	.8	4.4	.....	4.4	75.8	.....	75.8	65.1	.....	65.1
Accelerating from rest to 15 M. P. H., level	1.040	.....	1.040	9.2	.....	9.2	3.3	.....	3.3	4.7	.....	4.7	.7	.....	.7	2.4	.....	2.4	79.7	.....	79.7	53.3	.....	53.3
Running 20 M. P. H., level	.....	1.470	1.470	.....	9.4	9.4	.....	1.3	1.3	.....	7.1	7.1	.....	.7	.7	.....	3.1	3.1	.....	78.4	78.4	.....	102.8	102.8
Running 15 M. P. H., level	1.000	1.226	1.130	8.9	8.7	8.8	2.1	1.7	1.9	6.4	7.2	6.8	1.0	1.4	1.2	3.3	2.7	3.1	78.3	78.3	78.2	62.5	87.7	77.2
Running 10 M. P. H., level	.830	.848	.840	8.9	8.4	8.6	2.0	1.6	1.8	7.7	7.7	7.7	.9	1.2	1.1	2.7	3.4	3.0	77.8	77.7	77.8	56.3	64.5	61.0
Running 3 M. P. H., level	.640	.....	.640	7.6	.....	7.6	2.3	.....	2.3	7.9	.....	7.9	1.4	.....	1.4	3.8	.....	3.8	77.0	.....	77.0	50.1	.....	50.1

W — 5 trucks tested under winter conditions.
S — 7 trucks tested under summer conditions.
A — All tests.

TABLE 18

CLASS 4

Average gasoline consumption, exhaust gas analyses and quantity of carbon monoxide for trucks one and one-half to three tons, inclusive, capacity; tested under summer conditions. Results of full load tests.

TEST CONDITION	Gasoline used, gal. per hour at 60° F.	EXHAUST GAS ANALYSES, PER CENT (BY VOLUME)						Carbon monoxide cu. ft. per hour at 65° F. 29.92" Hg.
		Carbon dioxide (CO_2)	Oxygen (O_2)	Carbon monoxide (CO)	Methane (CH_4)	Hydrogen (H_2)	Nitrogen (N_2)	
Running 15 M. P. H. down 3% grade*	.950	5.8	7.3	5.9	2.2	1.5	77.3	65.8
Running 10 M. P. H. down 3% grade.	.789	6.5	6.5	5.5	1.9	1.2	78.4	52.1
Running 6 M. P. H. down 3% grade..	.463	6.5	8.5	3.2	1.5	.9	79.4	24.3
Running 15 M. P. H. up 3% grade*.	2.487	10.5	.6	5.4	.8	2.1	80.6	130.1
Running 10 M. P. H. up 3% grade..	2.359	9.8	.8	6.7	.8	2.8	79.2	149.6
Running 6 M. P. H. up 3% grade...	1.689	9.5	.9	6.9	.7	3.1	78.9	114.3
Running 15 M. P. H. on level grade*.	1.694	9.6	1.6	5.9	1.0	2.1	79.8	98.3
Running 10 M. P. H. on level grade..	1.497	8.6	1.6	7.2	1.1	3.1	78.2	110.0
Running 6 M. P. H. on level grade..	.994	8.6	1.8	7.3	1.0	3.3	78.0	72.7

Results unless otherwise noted are average of tests on 22 trucks.

* Results, averages of tests on 15 trucks under these test conditions.

TABLE 19

CLASS 5

Average gasoline consumption, exhaust gas analyses, and quantity of carbon monoxide for trucks three and one-half to four and one-half tons, inclusive, capacity; tested under summer conditions. Results of full load tests

TEST CONDITION	Gasoline used, gallons per hour, at 60° F.	EXHAUST GAS ANALYSES, PER CENT BY VOLUME						Carbon monoxide, cu. ft. per hour at 65° F. 29.92" Hg.
		Carbon dioxide (CO_2)	Oxygen (O_2)	Carbon monoxide (CO)	Methane (CH_4)	Hydrogen (H_2)	Nitrogen (N_2)	
Running 15 M. P. H. down 3% grade*	1.525	8.6	3.7	5.4	1.4	1.7	79.2	88.9
Running 10 M. P. H. down 3% grade.	1.236	7.4	4.3	6.6	1.7	2.3	77.7	89.0
Running 6 M. P. H. down 3% grade..	.705	6.2	6.8	5.7	1.6	1.9	77.8	49.6
Running 15 M. P. H. up 3% grade..	4.194	11.3	.5	4.1	.6	1.5	82.0	181.7
Running 10 M. P. H. up 3% grade..	3.522	10.4	.5	6.1	.6	2.7	79.7	88.5
Running 6 M. P. H. up 3% grade...	2.200	9.8	.6	6.9	.6	3.1	79.0	148.1
Running 15 M. P. H. on level grade*	2.663	10.4	1.1	4.6	.8	1.7	81.4	126.6
Running 10 M. P. H. on level grade..	2.049	8.9	1.1	7.6	.9	3.2	78.3	149.3
Running 6 M. P. H. on level grade..	1.351	9.3	1.0	7.2	.8	3.2	78.5	92.0

Results unless otherwise noted are average of tests on 16 trucks.

* Results, averages of tests on 5 trucks, under these test conditions.

TABLE 20

CLASS 6

Average gasoline consumption, exhaust gas analyses and quantity of carbon monoxide for trucks five tons and over capacity, tested under summer conditions. Results of full load tests

TEST CONDITION	Gasoline used, gallons per hour, at 60° F.	EXHAUST GAS ANALYSES, PER CENT BY VOLUME						CO cu. ft. per hour at 65° F. 29.92" Hg.
		Carbon dioxide (CO_2)	Oxygen (O_2)	Carbon monoxide (CO)	Methane (CH_4)	Hydrogen (H_2)	Nitrogen (N_2)	
Running 10 M. P. H. down 3% grade.	1.089	6.6	6.6	5.3	2.2	1.3	78.0	70.7
Running 6 M. P. H. down 3% grade..	.756	6.7	6.6	5.2	2.3	1.4	77.8	48.1
Running 10 M. P. H. up 3% grade..	3.967	11.1	.6	4.9	.7	1.9	80.8	199.3
Running 6 M. P. H. up 3% grade...	2.712	10.2	.6	6.1	.7	2.7	79.7	163.3
Running 10 M. P. H. on level grade..	2.425	8.7	1.6	7.1	1.2	2.8	78.6	167.5
Running 6 M. P. H. on level grade..	1.644	8.4	1.7	7.7	1.0	3.5	77.7	124.9

Results, averages of tests on 18 trucks.

Therefore, from theoretical considerations, the New York gasolines may give slightly lower percentages of carbon monoxide; however, practical considerations based on the tests at Pittsburgh made with high test gasoline and the lower grade of " motor gas " indicate no consistent difference in exhaust gas composition due to quality of gasoline used.

RESULTS OF TESTS

A summary of the average results of the tests on 101 passenger cars and trucks are given in tables 10–20 inclusive, and in Figures 8–13 inclusive. The average gasoline consumption, exhaust gas composition, and volume of carbon monoxide discharged is given for each class of motor vehicles for both summer and winter conditions for passenger cars and light trucks. Heavy trucks were tested under summer conditions only. The results shown in tables 10–15, inclusive, are averages of two *tests, one with no load other than the chauffeur, two observers and fifty pounds of apparatus, and the other with a load of full rated capacity.

The results of tables 16–20 inclusive represent the full load tests only. It was deemed desirable to present the results of the tests under both full load and average load conditions as the tunnel traffic may exceed an average load of one-half capacity, although it will certainly not exceed the full load capacity of all vehicles.

DISCUSSION OF RESULTS

It will be noted from the plotted results that the average percentage of carbon monoxide for each class of vehicles varies between five per cent as a minimum and nine per cent as a maximum. except in the heavy truck class where the variation is between four per cent minimum and eight per cent maximum, the range of variation being the same. The larger percentages tend to be produced when the engine is racing, idling or running on light load on the low gear at three miles per hour and on the low speed level grade tests for summer conditions. However, the greatest

* Except the five-passenger cars which were tested with average load only, consisting of three men and apparatus

amount of carbon dioxide per hour is generated under conditions of greatest load, i. e., when accelerating or running up grade at the highest speed.

The relative quantity of carbon monoxide produced depends primarily on the gasoline consumption as shown at a glance by the similar rise and fall of the "gasoline" and "cubic feet of carbon monoxide" curves.

The average percentage of carbon monoxide under all conditions of test for each class of vehicles was five-passenger cars, 6.4; seven-passenger cars, 7.1; trucks up to one and one-half tons capacity, 6.9; trucks one and one-half tons inclusive, 5.8; trucks three and one-half to four and one-half tons inclusive, 6.8; trucks five tons and over, 6.5. The average percentages of carbon monoxide obtained on these tests is practically the same as were obtained by Hood, Kudlich and Burrel* in tests of gasoline mine locomotives with carburetors adjusted for maximum power. They found that when the maximum power was being developed the gases usually contained from five to seven per cent carbon monoxide, and that the carbon monoxide content could be increased to as much as nine per cent without reducing the power appreciably.

These investigators have also shown that the proportion of carbon monoxide in exhaust gases varies from zero to about fourteen per cent, the amount depending on a number of variables, chief of which are:

(1) Ratio of air to gasoline.
(2) Completeness of vaporization and mixing.
(3) Speed of engines.
(4) Temperature of air and jacket water.
(5) Quality and time of spark.
(6) Degree of compression.
(7) Quality of gasoline or motor fuel.

In view of this large number of variables it is not surprising that extremely large variations in exhaust gas composition were obtained in testing motor vehicles taken from ordinary service without any adjustment prior to test and driven in a variable manner with foot accelerator or hand throttle by different drivers over an approximately smooth course, but yet one with some rough places requiring opening and closing the throttle to maintain a constant speed.

It is, therefore, not possible to draw conclusions on the effect on exhaust gas composition of the various factors just enumerated, except with regard to the first one, namely, ratio of air to gasoline, or carburetor adjustment.

Effect of Carburetor Adjustment: A study of all the tests made shows that the variation in exhaust gas composition due to carburetor adjustment is far greater than any other factor; they do not throw much light on the advantage of any particular make or type of carburetor, nor should any conclusions be drawn as to the merits or demerits of any particular make of car. Table 21 gives a comparison of the best and poorest tests obtained on several well known makes of passenger cars and trucks. Car No. 1 had the best gas analysis, and greatest mileage of any car tested. Car No. 44, also a five-passenger car, had the poorest gas analysis and the lowest mileage in its class. Both cars operated without any apparent difficulty throughout the tests. Car No. 11 did not operate smoothly and lacked flexibility at low speed due to the mixture being too lean. However, the mileage per gallon of gasoline was much higher than the other cars in the same class. At speeds above fifteen miles per hour it operated smoothly and gave a good illustration of the tremendous quantity of fuel that may be saved by using lean mixtures. It should be noted that in each case the car with the leaner mixture shows the largest mileage per gallon of gasoline. The percentage increase in mileage ranges from 36 to 106 per cent.

The effect of various carburetor adjustments of an individual car is shown in Table 22.

* Hood, O. P., Kudlich, R. H., and Burrell, G. A., Gasoline mine locomotives in relation to safety and health, Bureau of Mines Bulletin 74, pp. 66-68.

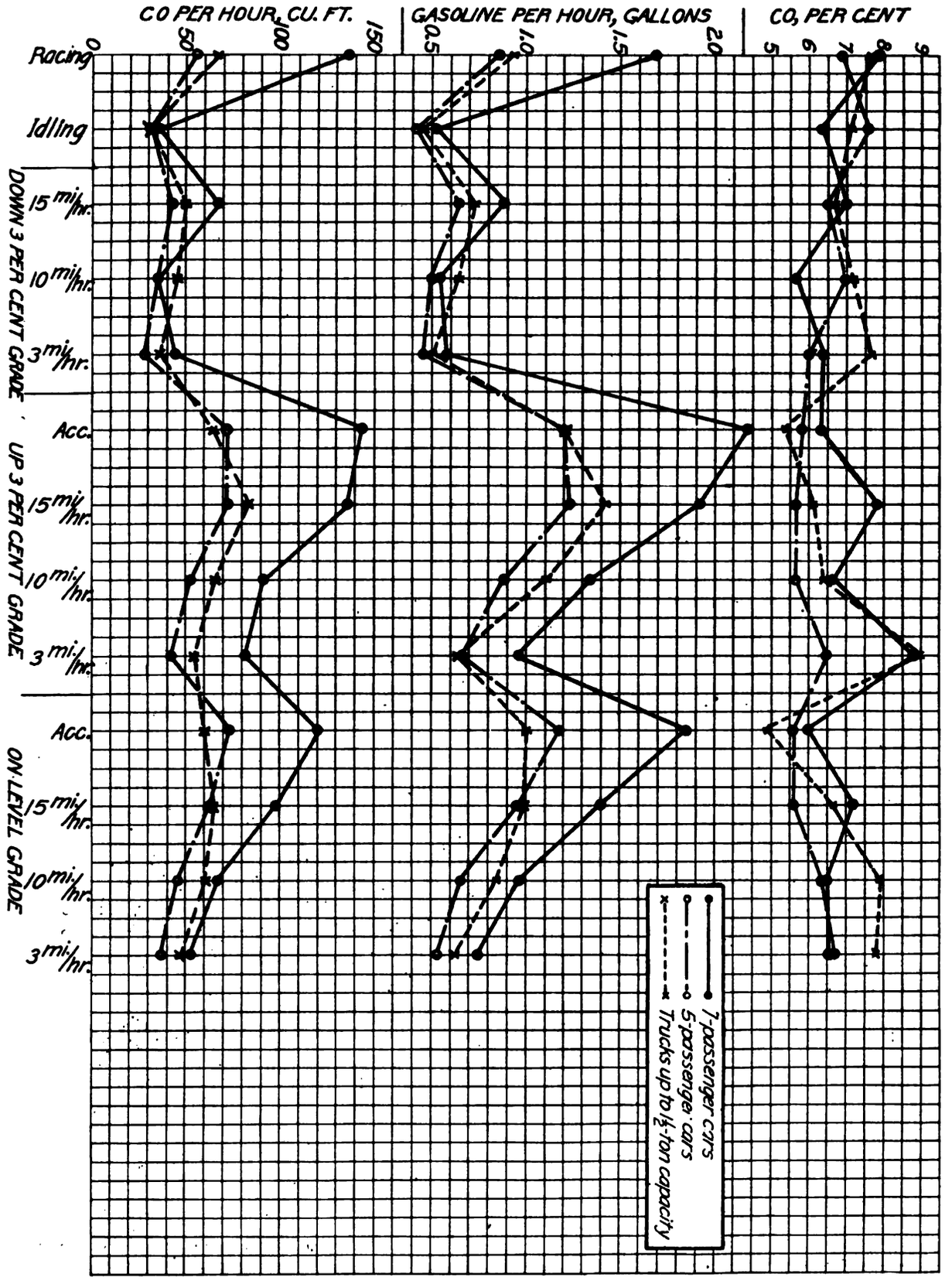

CO PER HOUR, CU. FT.
GASOLINE PER HOUR, GALLONS
CO, PER CENT
0
50
100
150
0.5
1.0
1.5
2.0
5
6
7
8
9
Racing
Idling
DOWN 3 PER CENT GRADE
15 mi./hr.
10 mi./hr.
3 mi./hr.
UP 3 PER CENT GRADE
Acc.
15 mi./hr.
10 mi./hr.
3 mi./hr.
ON LEVEL GRADE
Acc.
15 mi./hr.
10 mi./hr.
3 mi./hr.
7-passenger cars
5-passenger cars
Trucks up to ½-ton capacity

Figure 8

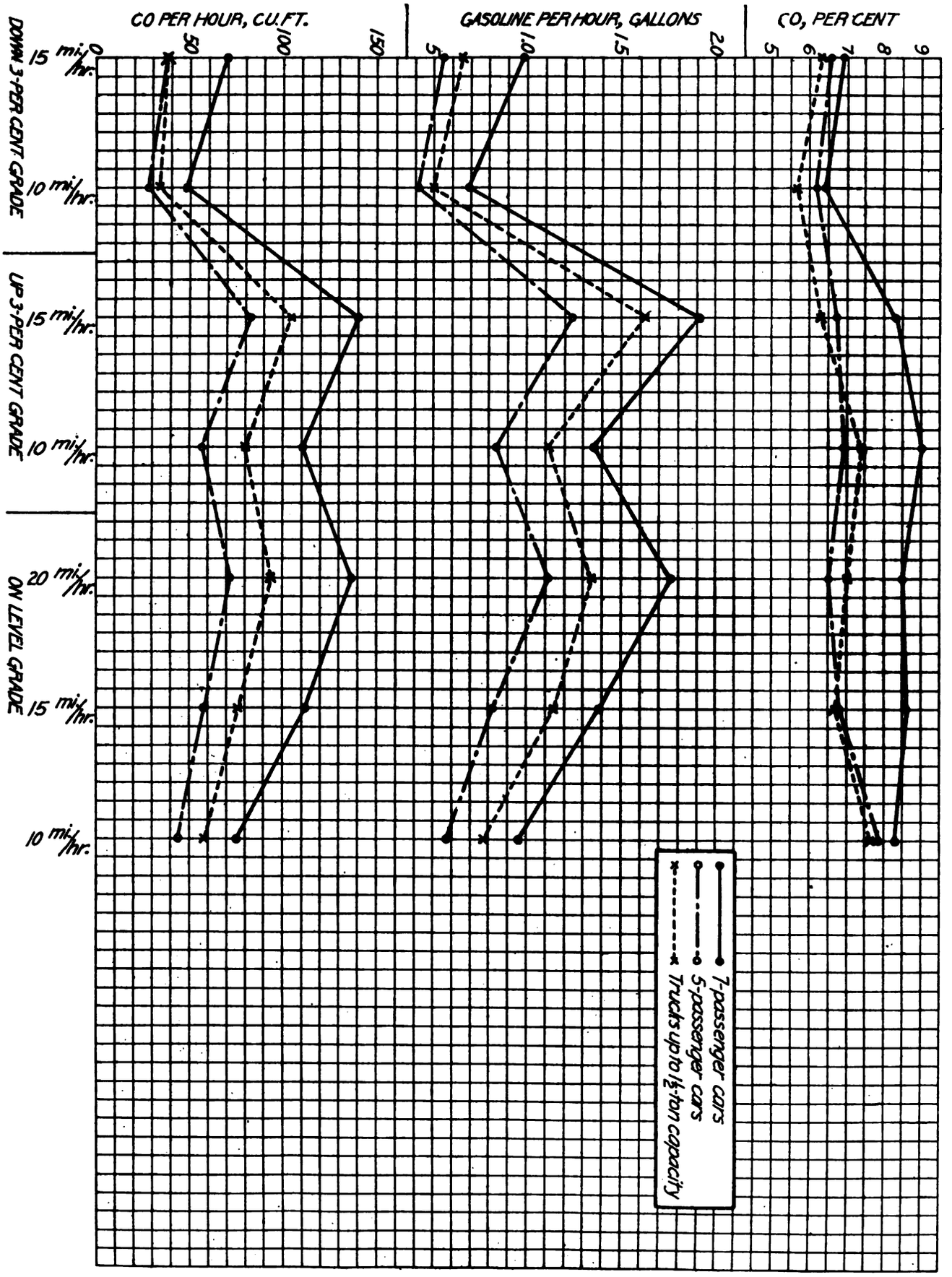


Figure 9.— Curves showing average gasoline consumption, per cent and quantity of carbon monoxide for 5 passenger, 7 passenger cars and trucks up to 1½ tons capaicty, tested under summer conditions. Average of light and full load tests.

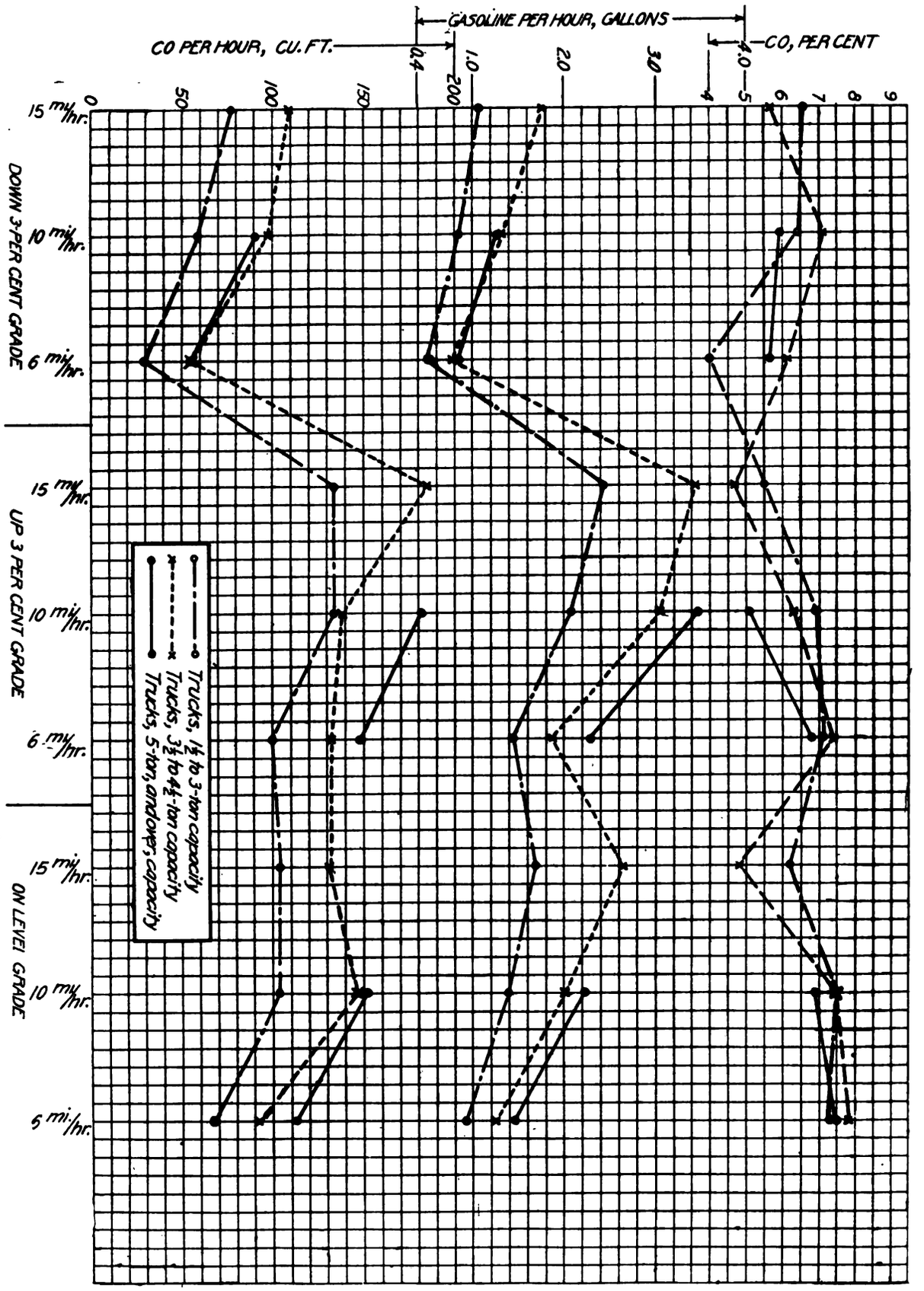


Figure 10.— Curves showing average gasoline consumption, per cent. and quantity of carbon monoxide for trucks 1½ to 3 tons capacity, inclusive, 3½ to 4½ capacity and 5 tons capacity and over, tested under summer conditions. Average of light and full load tests.

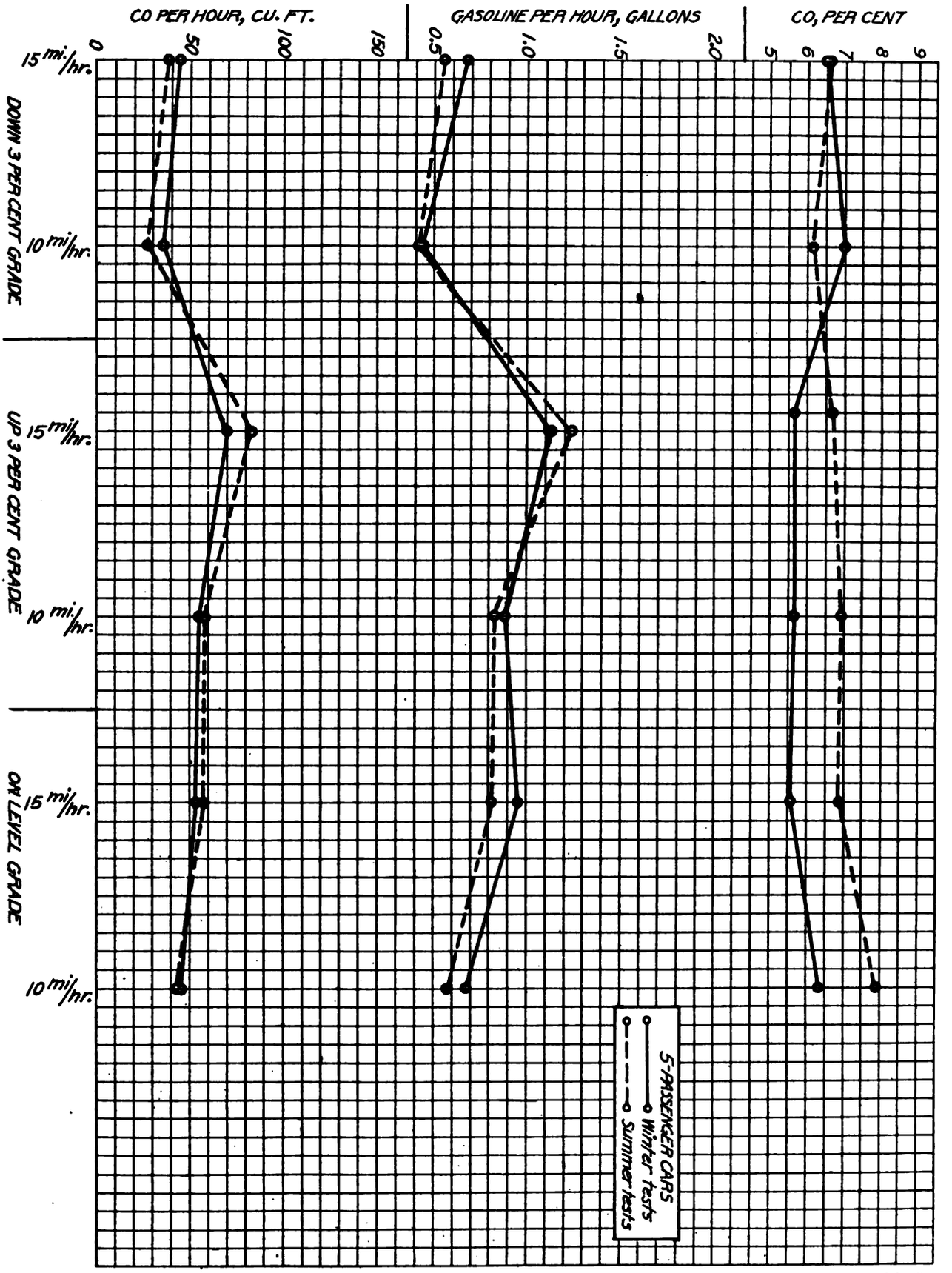


Figure 11.— Curves showing gasoline consumption, per cent and quantity of carbon monoxide for 5 passenger cars, tested under winter and summer conditions, with average load.

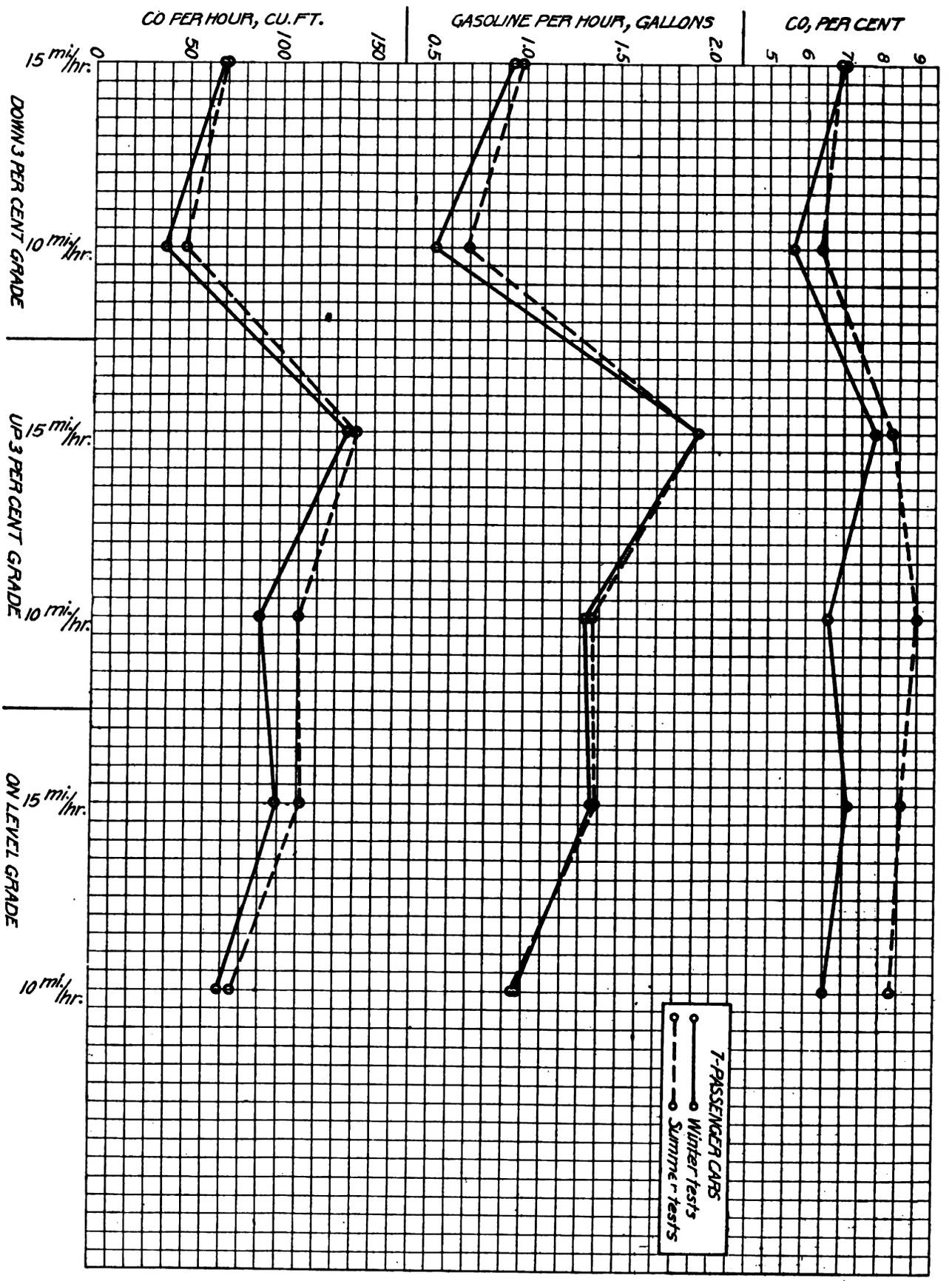


Figure 12.— Curves showing gasoline consumption, per cent and quantity of carbon monoxide for 7-passenger cars tested under winter and summer conditions, average of light and full load tests.

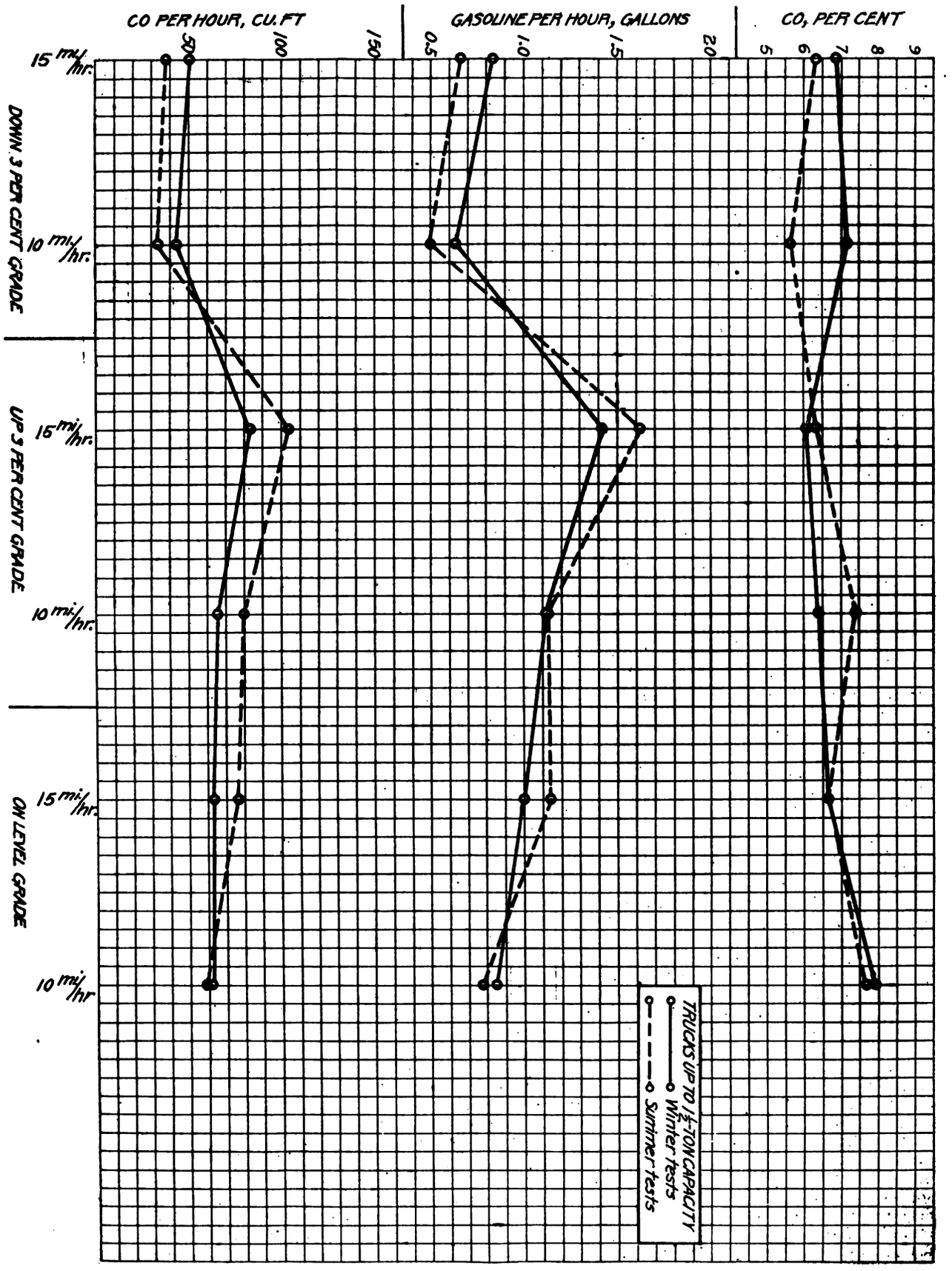


Figure 13.— Curves showing gasoline consumption, per cent and quantity of carbon monoxide for trucks up to 1½ tons capacity, tested under winter and summer conditions, average of light and full load tests.

TABLE 21

Showing Best and Poorest Results Obtained on several Representative Makes of Passenger Cars and Trucks.

Car No.	Make of car	Type of Car	Speed level grade M. P. H.	Miles per gallon	Per cent increase in mileage	Per cent completeness of combustion	Exhaust Gas Analyses Per Cent by Volume					Air to gasoline, ratio, pounds
							CO_2	O_2	CO	CH_4	H^2	
1.....	C	5-passenger.....	15	27.30	105.8	100	13.0	2.6	....	....	....	16.7
9.....	C	5-passenger.....	15	13.26	.....	84	11.8	.8	3.7	.3	1.6	13.5
11.....	G	7-passenger.....	15	18.61	66.8	93	9.3	5.4	1.3	....	.1	20.1
10.....	G	7-passenger.....	15	11.16	.....	61	7.5	2.1	9.3	1.4	4.0	10.7
84.....	X	¾ T. Truck.....	15	15.39	44.5	90	10.7	3.9	1.7	.5	.2	16.6
76.....	X	¾ T. Truck.....	15	10.66	.....	59	7.1	.7	10.7	1.0	5.1	10.3
38.....	Y	3½ T. Truck.....	10	6.55	36.2	87	12.9	.3	1.9	.8	.4	13.9
57.....	Y	3½ T. Truck.....	10	4.81	.....	65	7.5	.8	10.6	1.0	4.9	10.2
44.....	D	5-passenger.....	15	10.26	.....	49	5.3	1.0	13.2	1.9	7.1	9.0

All cars loaded.

TABLE 22

EFFECT OF CARBURETOR ADJUSTMENT ON GASOLINE CONSUMPTION AND EXHAUST GAS ANALYSIS

Four-cylinder roadster, engine four and one-eighth-inch bore by four and one-half-inch stroke. Johnson carburetor; intake air and manifold heated; using gasoline 66.4 degrees Baume, distillation 10 per cent, 127 degrees F. 50 per cent, 225 degrees F., dry, 441 degrees F., average 230 degrees F. Tests at fifteen miles per hour ascending a 3 per cent grade on asphalt in good conditions.

Carburetor Adjustment Needle Valve Turns	Gasoline Consumption		Exhaust Gas Analysis, Per Cent						Pounds air per pound gasoline	Per cent completeness of combustion	Remarks
	Gallons per mile	Miles per gallon	CO_2	O_2	CO	CH_4	H_2	N_2			
1.....	.067	14.9	13.4	1.7	1.2	0.2	0.0	83.5	14.5	95	Exhaust clear, mixture too lean to operate without use of air choke.
1¼.....	.072	13.9	12.0	1.4	2.0	1.1	0.0	83.5	14.2	85	Exhaust clear, operation satisfactory. Air choke ¼ on during part of test.
1 7/16..... ...	.094	10.6	10.2	0.3	6.4	0.8	2.4	79.9	11.8	74	Exhaust slightly smoky; operation satisfactory. Car aad good "pick-up".
1½.....	.1142	8.8	6.5	1.2	11.6	1.0	6.4	73.3	9.9	56	Smoky exhuast, mixture seemed too rich for satisfactory operation.

Before putting this car through the standard series of road tests the driver, an automobile mechanic, was asked to place the carburetor in good adjustment. He set it after the engine was warmed up to running conditions, at one seven-sixteenths turns of the needle valve. As shown, in the table this setting produced 6.4 per cent carbon monoxide and 10.2 per cent carbon dioxide, a little better than the average analysis of all cars tested. Tests were then repeated under identical conditions with both richer and leaner settings. It was found that one and one-quarter turns of the carburetor needle gave twelve per cent CO. and two per cent CO; and thirty-one per cent greater mileage; also the car operated satisfactorily.

This test is typical of the great majority of the passenger cars and trucks tested, they were invariably adjusted safely on the rich side for greatest flexibility of operation rather than for maximum economy of gasoline.

Reasons for Existing use of Rich Mixtures: One pound of ordinary motor gasoline of today such as was used in the tests just described required approximately fifteen pounds of air for complete combustion. The maximum thermal efficiency is obtained at about sixteen pounds* of air to one pound of gasoline and the maximum power with twelve to thirteen pounds of air.† Herein lies the reason for the use of rich mixtures. The average driver demands first of all power and flexibility of operation. He sets his carburetor adjustment rich enough to give good operation with a cold engine and for slow driving in heavy traffic, with plenty of reserve power for hill climbing and bad road. If he errs somewhat on the rich side it does not become manifest in loss of power, but only in the increased gasoline consumption which in many instances does not concern him at all. An inspection of the average thermal efficiency and power curves of Figure 14 (after Berry) shows that the proportion of air in the mixture can be reduced to nine pounds of air to one pound of gasoline with a loss of only nine per cent in power, although economy and efficiency are tremendously reduced.

Figure 15 shows the relation between the air-gasoline ratios and the percentage carbon monoxide in the exhaust gas for the first twenty-three passenger cars and trucks tested at fifteen miles an hour running up a three per cent grade. The air ratios varied from fifteen and eight-tenths with about one per cent carbon monoxide, to nine and seven-tenths pounds air with twelve and three-tenths per cent carbon monoxide. The average air-gasoline ratio was twelve and four-tenths with an average carbon monoxide per cent of six and three-tenths, practically the exact figure for maximum power. Obviously, carburetors are adjusted in practice for maximum power and not for maximum thermal efficiency and economy of gasoline.

The average loss of gasoline due to the continuous operation of a car at the point of maximum power is shown in the following computations from average exhaust gas analyses, heat in the gasoline and heat in the unburned exhaust gas constituents:

	Average composition of exhaust gas, by volume from tests of 23 cars, at fifteen miles per hour	
	Level grade per cent	Ascending 3% grade, per cent
Carbon dioxide	8.9	9.6
Oxygen	2.3	1.3
Carbon monoxide	6.3	6.4
Methane	0.9	0.6
Hydrogen	.3.0	2.9
Nitrogen	78.6	79.2
	100%	100%

Cubic feet exhaust gases at 65° and 29.92″ Hg. 988

Composition of Gasoline:

Sp. Gr.	0.713	
Carbon	84.3	per cent
Hydrogen	15.7	per cent
Calorific value	21,300 B. T. U. per lb. = 130,000 B. T. U. per gallon.	

Exhaust gas from one gallon on level grade tests contains:

$$988 \times 6.3 = 62.2 \text{ cubic feet CO}$$
$$988 \times 0.9 = 9.1 \text{ cubic feet } CH_4$$
$$988 \times 3.0 = 2.9 \text{ cubic feet } H_2$$

* With this mixture the engine develops about 85 per cent of its maximum power.

† Berry, O. C., Mixture requirements of automobile engines. Jour. of the Soc. of Automobile Engineers, vol. 5, 1919, page 364.

Total heat in unburned gases per gallon gasoline:

$$\begin{aligned} 62.2 \times 320^{*} &= 19{,}900 \text{ B. T. U.} \\ 9.1 \times 1000 &= 8{,}900 \text{ B. T. U.} \\ 29.6 \times 322 &= 9{,}600 \text{ B. T. U.} \\ & 38{,}400 \text{ B. T. U.} \end{aligned}$$

$$\frac{38400}{130000} = 29.5 \text{ per cent}$$

Twenty-nine and five-tenths per cent of the total heat of the gasoline goes out in the exhaust in the form of combustible gases.

* Gross B. T. U. per cubic foot at 65° F. and 29.92 inches Hg.

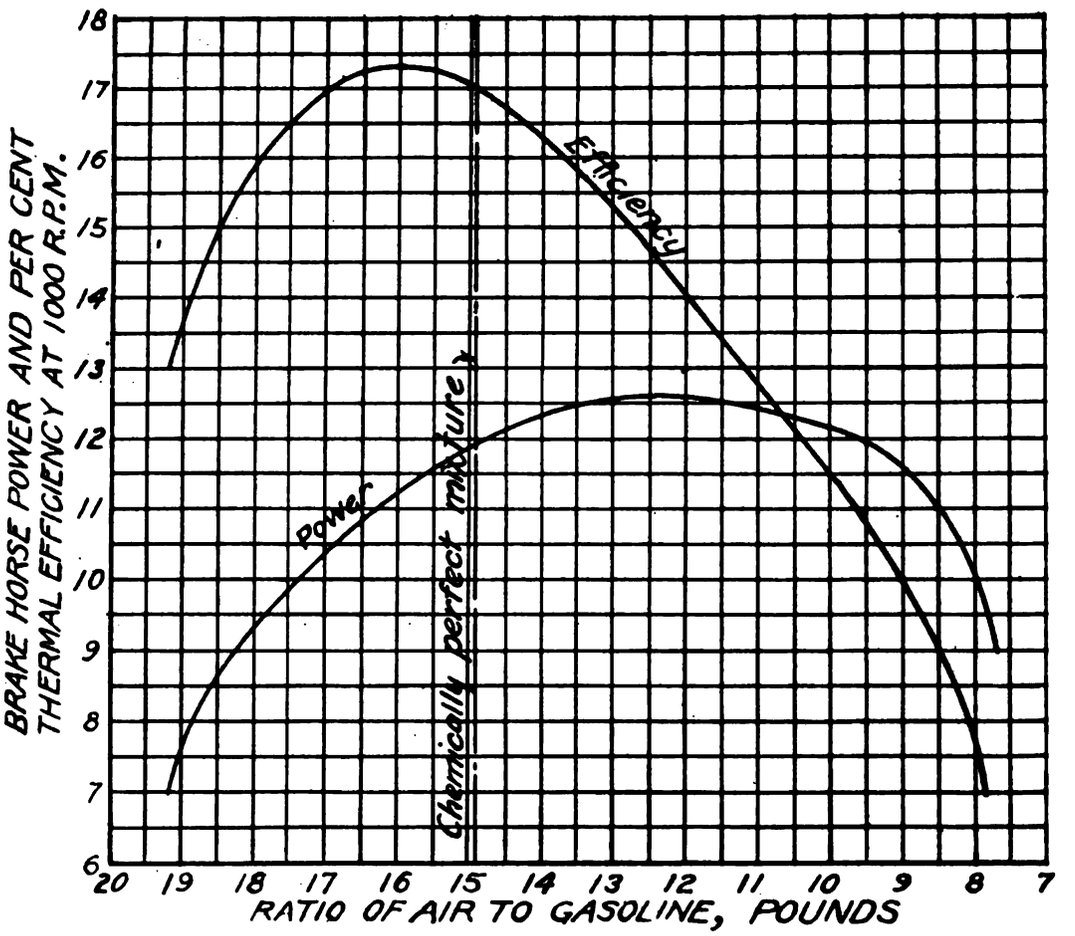


Figure 14.— Curves showing relation of air to gasoline ratio in pounds: to power and thermal efficiency of 4¼ x 4½-inch stroke Willys-Knight 4-cylinder motor at 1000 R.P.M. After Berry.

RELATIVE PROPORTION OF CARBON MONOXIDE UNDER WINTER AND SUMMER CONDITIONS

Figures 11, 12 and 13 show comparisons of the quantities of carbon monoxide produced by passenger cars and trucks under winter and summer conditions. It will be noted that there is a marked tendency toward higher percentages of carbon monoxide in the summer tests, although this higher proportion of carbon monoxide in the exhaust is offset to some extent by lower gasoline consumption. Most of the winter tests were run on streets covered with snow and ice. The snow was well packed but the course was slippery and chains were used in all such tests. The higher winter gasoline consumption is undoubtedly due to the greater power required.

A comparison of the average cubic feet of carbon monoxide produced per hour for five-passenger cars, seven-passenger cars, and light trucks, running at ten and fifteen miles per hour, on the level and up three per cent grades, shows an increase under summer conditions for each class of seven, eleven and sixteen per cent, respectively.

It is believed that most carburetors are set for good operation under winter conditions and then are left unchanged for summer use, thus tending to produce a richer mixture when the weather gets warmer.

As the tunnel atmosphere will be considerably warmer than the outside air in the winter, the results of the summer tests should more nearly approximate the average tunnel conditions for the entire year. If the tunnel atmosphere becomes unduly heated from the automobile exhaust during the hot summer months it is probable that even higher quantities of carbon monoxide will be produced in the tunnel than were obtained in the summer tests on the road.

EXPLOSIBILITY OF MIXTURES OF GASOLINE VAPOR AND AIR*

Considerable work on the limits of inflammability of mixtures of gasoline vapor and air which has a bearing on this subject has been done by G. A. Burrell and H. T. Boyd, of the Bureau of Mines.† Briefly the experiments may be summarized thus:

With a 100 c.c. Hempel explosion pipette and ignition from the top with a small induction spark, the lower limit of complete inflammation was between one and nine-tenths and two per cent of gasoline vapor, and the upper limit was between five and two-tenths and five and three-tenths per cent. The gasoline used was a refinery distillate of seventy-three degrees Baume specific gravity. With ignition from the bottom, other conditions being the same, the low limit was between one and five-tenths and one and six-tenths per cent. With a 2,800 c.c. vessel, with ignition from the bottom by means of an electric flash produced by pulling apart two wires through which a current of seven amperes at 220 volts was flowing, the low limit was between one and four-tenths and one and five-tenths per cent and the high limit between six and six and four-tenths per cent of gasoline vapor.

Further experiments were made to determine whether or not the inflammable limits of gasoline air mixture differed for gasoline of different grades; that is, whether the low limit as determined for gasoline having a specific gravity of seventy-three degrees Baume was different from the low limit of a gasoline (or naphtha) having a specific gravity of, say, fifty-nine degrees Baume. It was found that complete inflammation took place in a mixture containing one and five-tenths per cent of gasoline vapor (ignition from the bottom), or practically the same as the gasoline of higher specific gravity. It was found impossible to obtain a mixture containing too much gasoline to explode at the temperature of the laboratory, twenty-one degrees C. The highest mixture obtainable, four and six-tenths per cent of gasoline vapor, completely inflamed. In other words, the vapor

* Hood, O. P., Kudlich, R. H., and Burrell, G. A., Gasoline mine locomotives in relation to safety and health. Bulletin 74, Bureau of Mines, 1915, pp. 69–70.

† Burrell, G. A., and Boyd, H. T., The limits of inflammability of mixtures of gasoline vapor and air. Tech. Paper 120, Bureau of Mines, 1915, 18 pages.

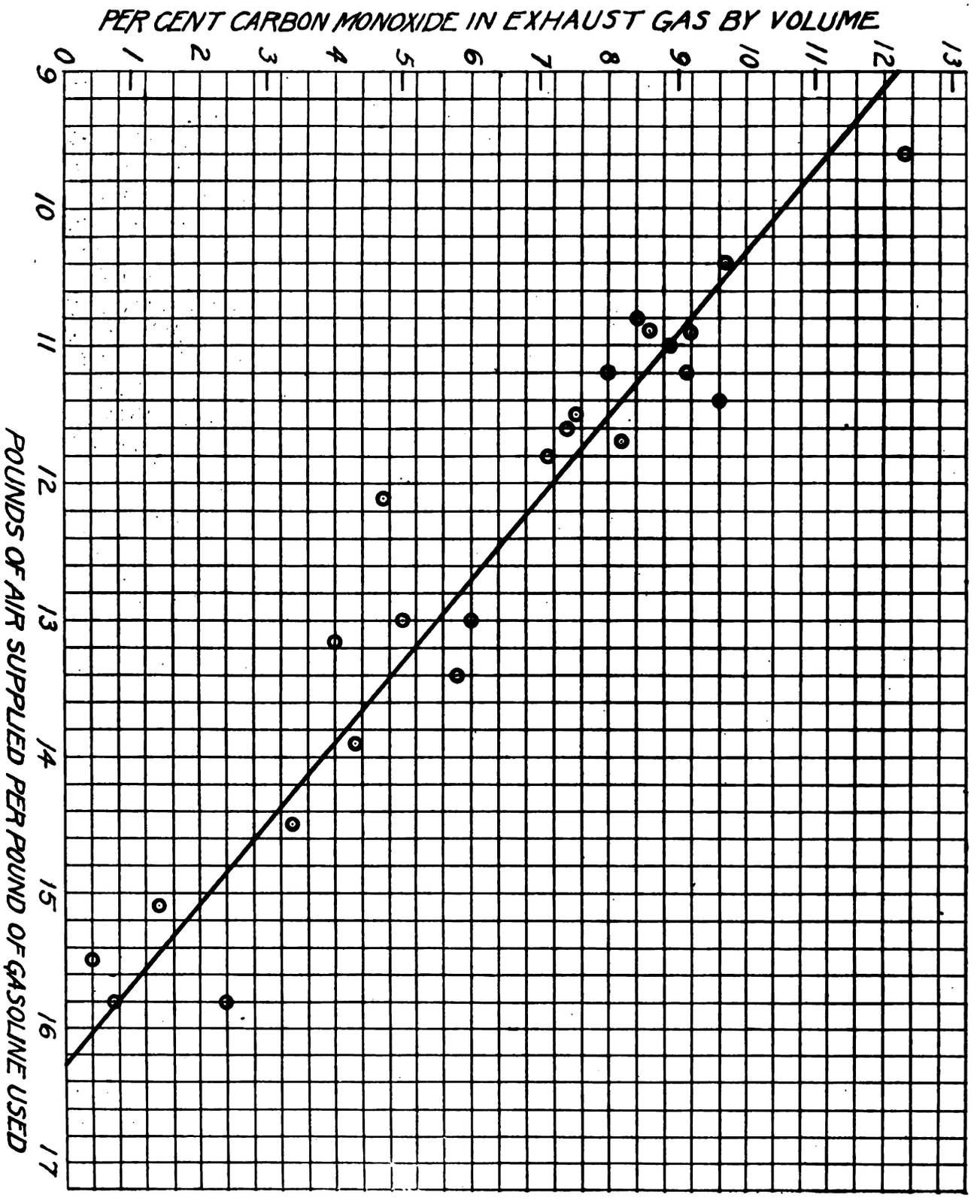


Figure 15.— Curve showing relation between air-gasoline ratios and percentage of carbon monoxide in exhaust gases for 23 passenger cars and trucks when running up grade at 15 miles per hour.

pressure of this particular naphtha at twenty-one degrees C. was 740 x 0.046 = 33 mm. of mercury. It would have been possible, of course, by maintaining higher temperatures all through the experiment, to obtain mixtures of higher gasoline vapor content.

From these experiments it is seen that only one and five-tenths per cent by volume of gasoline vapor in air is required to produce an inflammable mixture. Therefore, all sumps in the tunnel must be thoroughly ventilated to prevent any accumulation of gasoline vapors. In the tunnel proper where a vigorous degree of ventilation is maintained there will be no danger from explosion as shown from the following quoted from Hood, Kudlich and Burrell on " Gasoline Mine Locomotives".*

" Explosion proportions of gasoline vapor and moving air are very difficult to attain in a mine entry. In order to test the rate of evaporation of gasoline in a mine entry a shallow pan, eighteen and one-half inches in diameter, loosely filled with road ballast, was placed in an entry so that the air current passed over it. Gasoline was poured over this ballast, creating a condition similar to that which would exist were a quantity of gasoline spilled in an entry. With a current of air passing at an average velocity of 668 feet per minute over the pan the gasoline was vaporized at the rate of 0.662 pound per hour or 0.01037 pound per minute. To produce an explosive mixture, this amount of gasoline vapor must be mixed with not more than 2.85 cubic feet of air As the diameter of the pan was eighteen and one-half inches and the velocity of the air current 668 feet per minute, this gasoline vapor must be confined to a stratum $\frac{2.85}{668 \times \frac{18.5}{12}}$ or 0.0028 foot thick to produce an explosive mixture, a condition which obviously could not occur in an open entry in the presence of a current of air necessary to produce that high rate of vaporization. In an inclosed room or in dead air the conditions, of course, would be very different.

" The danger, therefore, is evidently not so much from explosion as from fire, so long as a current of air is passing sufficient to dilute and carry away the gasoline vapors as quickly as they are given off.

" If gasoline is spilled in a closed room — for example, in a pump room or engine room where little or no air is circulating — the proper proportions for an explosive mixture of gasoline vapor and air are easily obtained and an explosion may result if a naked light is brought into the room. All closed rooms where gasoline is used or stored should therefore be amply ventilated to prevent any accumulation of mixtures of gasoline vapor and air, and only safe incandescent electric lights or safety lamps should be used for illumination."

Summary:

The road tests on 101 motor vehicles for the purpose of determining the amount and composition of motor exhaust gas from automobiles and trucks of various sizes when operated on grades and at speeds similar to those that will prevail in vehicular tunnels have shown that:

(1) The exhaust gas composition of individual machines varies greatly, and that the controlling factor is the air-gasoline ratio produced by the carburetor adjustment.

(2) The percentage of carbon monoxide for the majority of cars lies between five and nine per cent.

(3) The average percentage of carbon monoxide for the first twenty-three cars tested was six and seven-tenths per cent, which is practically the percentage of carbon monoxide corresponding to an air-gasoline ratio of twelve and four-tenths ratio for developing maximum power.

(4) The average percentage of carbon monoxide for each class of vehicles under various conditions of test is given in the tables and curves.

(5) The average cubic feet of carbon monoxide for each class of motor vehicles under certain conditions is given in the tables and curves.

(6) The combustible gas in the average automobile exhaust from one gallon of gasoline amounts to thirty per cent of the total heat in a gallon of gasoline.

* Loc. Cit., pp. 19.

(7) The great majority of motor cars and trucks are operated on rich mixtures suitable for maximum power but very wasteful from the standpoint of gasoline economy.

(8) On the average, carburetors are set in the winter and not changed in the summer, as shown by the higher percentages of CO found in the summer tests.

(9) The largest quantity of carbon monoxide will be produced in the three per cent grade sections of the tunnel. The carbon monoxide produced under summer conditions is somewhat greater than in winter conditions. Summer tests should be used in computing ventilation of tunnels, owing to the tunnel becoming heated from the hot exhaust gases.

Respectfully submitted,

(Signed) A. C. FIELDNER

Supervising Chemist

APPENDIX NO. 4

REPORT OF TUNNEL GAS INVESTIGATIONS, PROBLEM NO. 2 PHYSIOLOGICAL EFFECTS OF EXHAUST GASES

YANDELL HENDERSON

DEPARTMENT OF THE INTERIOR, BUREAU OF MINES, F. G. COTTRELL, DIRECTOR

REPORT ON TUNNEL GAS INVESTIGATIONS TO THE CHIEF ENGINEER OF THE NEW YORK STATE BRIDGE AND TUNNEL COMMISSION AND THE NEW JERSEY INTERSTATE BRIDGE AND TUNNEL COMMISSION. PROBLEM NO. 2 PHYSIOLOGICAL EFFECTS OF EXHAUST GASES, YANDELL HENDERSON, PHYSIOLOGIST IN CHARGE.

OR

The Physiological Principles Applicable to the Ventilation of any Chamber, Tunnel, Mine, Fire Room, Garage, or Other Space in which the Air is Contaminated with Carbon Monoxide, and the Particular Application of these Principles to a Tunnel for Motor Vehicles When the Time of Passage is Brief.— By Yandell Henderson, Howard W. Haggard, Merwyn C. Teague, Alexander L. Prince, and Ruth M. Wunderlich.

INTRODUCTION

The increasing use of the gasoline engine in a widening diversity of fields has brought with it corresponding problems concerning the influence of exhaust gases upon the health not only of the men in immediate charge of the machines but of the general public as well.

The Bureau of Mines has already carried out studies upon a number of these problems. These studies have dealt with the use of traction engines in coal mines, the vitiation of air in small garages; and many investigations have been made on the vitiation of the air in coal mines, and the determination of standards for the allowable vitiation requisite for safety.

The plan to construct tunnels under the Hudson River between New York and Jersey City for the use principally of motor vehicles has raised several problems which have however never previously been extensively investigated. Whereas the conditions in coal mines and about gas producer plants apply only to healthy men, the conditions which will prevail in the tunnel under the Hudson River will affect the general public. Not only healthy adults but children and even invalids on their way to a hospital will be transported thru it. Soldiers may march thru it. The amount of traffic is likely to be large even from the beginning, and to increase in a few years to the maximum capacity of the roadway. The total amount of exhaust gas discharged from passenger cars and trucks will therefore be considerable. The distance between the ventilating shafts at the pier heads on the two sides of the river will be somewhat more than 3000 feet, a distance greater than in any existing tunnel used by motor vehicles. The ventilation must be ample to prevent not only danger, but even slight discomfort, and must be managed in such a fashion as to avoid excessive wind velocities. The cost of installing ventilating fans will, in any case, be an appreciable item in the initial construction. The maintenance of artificial ventilation during the operation of the tunnel is likely to be one of the largest single items of continuing expense.

It will be readily seen that the investigations and formulations here presented are of much wider scope than merely the solution of the problem raised by the Hudson Tunnel. Vehicular tunnels are being very generally considered both as substitutes for bridges and as a means of decreasing distances and grades in highways in mountainous regions.

Furthermore, the results of these investigations apply almost equally well to conditions in garages and fire rooms, to the air around gas producers, smelters and blast furnaces, to dwellings in which there is an escape of illuminating gas, and in general to all places where men are exposed to the gaseous products of incomplete combustion.

Prior to this investigation the standards of allowable air vitiation with carbon monoxide have not been precisely defined. The investigations of Dr. J. S. Haldane, the eminent English authority, have dealt chiefly with questions of the safety of miners after mine explosions and fires. His attention has been directed generally therefore to the amount of carbon monoxide which would incapacitate, or seriously inconvenience a man, rather than to those amounts which are compatible with complete comfort and efficiency. For the London Underground Railways, however, he gave it as his opinion that a concentration of not more than one part of carbon monoxide in 10,000 of air was desirable. It is noteworthy, however, that he contemplated a possible period of exposure sufficient for the blood to approach equilibrium with this concentration in the air.

The standard hereinafter proposed appears at first sight distinctly higher than that originally suggested by Dr. Haldane. But when the short time of exposure in the proposed vehicular tunnels is taken into consideration it will be seen that the figures reached by the English investigator, and those in this report, for the amount of carbon monoxide absorbable without appreciable injury or discomfort are in quite close agreement.

It might appear that the ventilation of any closed space should be such as to furnish virtually as pure air as that of the city streets. In that case, this investigation would be unnecessary, and a standard of not more than one part of carbon monoxide in ten thousand of air might have been adopted. To have attempted, however, to ventilate a long tunnel like that under the Hudson River, or any similar closed space, so that the air would be virtually free from carbon monoxide, would perhaps have proved scarcely practicable. It would certainly have been extremely expensive. The wind velocities necessary in moving such a volume of air would cause discomfort to passengers and might even prove prohibitive of traffic.

The standards here established will very greatly reduce the expense of ventilation below that of one to ten thousand dilution, not only in the Hudson Tunnels, but in all future similar undertakings. These standards should prove valuable both to hygienists interested in safeguarding the public health and to engineers engaged in the design of a wide variety of projects both above and below ground.

FUNDAMENTAL CONSIDERATIONS

Altho carbon monoxide is the cause of more deaths than the total due to other gases, it is apart from a single reaction a physiologically inert and non-poisonous substance. This reaction is its combination with hemoglobin, the red coloring matter and oxygen carrying element of the blood. To whatever extent hemoglobin is so combined it is rendered incapable, until the carbon monoxide is again displaced, of transporting oxygen from the lungs to the tissues and organs of the body.

It is highly probable that all of the results of inhalation of carbon monoxide are due directly or indirectly to oxygen deficiency. Even when as in smoke fumes from explosives, and other incomplete combustions, other toxic substances are present, carbon monoxide is usually the chief cause of injury or death. The body of an adult man of average weight contains enough hemoglobin to hold about six hundred c.c. of oxygen. If completely saturated it would hold the same amount of carbon monoxide, one molecule of carbon monoxide replacing one molecule of oxygen in the blood. The absorption of six c.c. of carbon monoxide from the lungs produces then one per cent of saturation, and six-tenths c.c. abolishes one thousandth, or one-tenth per cent of the oxygen capacity. A fairly vigorous man breathes about eight liters of air a minute when sitting at rest, and roughly twice as much when walking at a good pace, or three times as much when hurrying, carrying a moderate load, or working at a rate that he can maintain for a considerable time. About twenty-five per cent of each breath merely enters the respiratory dead space, the mouth, nose, wind pipe, et cetera; and seventy-five per cent, or about 6000 c.c. of air a minute when the subject is sitting at rest, enters the lungs.

The unit in which various concentrations of carbon monoxide are commonly measured and expressed for purposes of ventilation, is one " part " or a certain number of " parts " of this gas

mixed with ten thousand times as much air. A " part " is a hundredth of one per cent of an atmosphere. Now .01 per cent of 6000 c.c. (the volume of air entering the lungs in a minute) of 0.6 c.c., and this in turn is 0.1 per cent of 600 c.c., the body's oxygen capacity. Evidently then, if all the carbon monoxide entering the lungs were to be absorbed, the blood would become saturated at the rate of 0.1 per cent per minute, or 1.0 per cent every ten minutes, per " part " of carbon monoxide in the air.

It appears that when a man begins breathing any low concentration of carbon monoxide mixed with air, absorption at very nearly this rate does occur, but only at first. The absorption of carbon monoxide by hemoglobin is an additive reaction, just as the absorption of oxygen is, indeed it is essentially the same reaction. This reaction is much like the union of oxygen and iron, for example, in the formation of iron oxide. Hemoglobin indeed contains iron and it is with the iron that both oxygen and carbon monoxide apparently unite. But it is the entire molecules of either gas, oxygen and carbon monoxide and not their separated atoms which seem to unite with hemoglobin. In this respect oxy-hemoglobin differs from an ordinary oxide, and the reaction of oxygen and hemoglobin is very easily reversible. It requires only a lowered oxygen pressure, without any reducing agent, to bring the gas off. It is this property of hemoglobin which enables the blood to take up oxygen in the lungs and to give it off to the working muscles and other tissues of the body.

The reaction of hemoglobin with carbon monoxide is more intense than with oxygen; and, as carbon monoxide is not consumed in the tissues; it can be eliminated from the blood only through the mass action of oxygen in the lungs. But it is quite erroneous to think that carbon monoxide causes directly any change in the blood other than a temporary replacement of oxygen and consequent asphyxia. It acts in a manner altogether different from the irritant and corrosive gases employed in war. It merely displaces and temporarily excludes oxygen from the blood up to a point depending upon the relative amounts of carbon monoxide and oxygen in the air breathed and the duration of exposure. But if thereafter the pressure of oxygen is high enough and that of carbon monoxide is low, or absent as in pure air, oxygen can likewise displace carbon monoxide and thus completely restore the oxygen carrying power of the hemoglobin. The amount of hemoglobin combined with each gas when air containing carbon monoxide is breathed for a long time is merely the expression of the equilibrium between forces which are the. tensions (partial pressures) of each gas in the air of the lungs and the chemical attraction of hemoglobin for each.

Hemoglobin attracts carbon monoxide about 300 times as strongly as it does oxygen. When blood is exposed for a sufficiently long time to an atmosphere containing a certain amount of oxygen, say twenty-one per cent of an atmosphere as in air, and one three-hundredth as much carbon monoxide diffusion and the mass actions of the two gases bring about a condition of equilibrium, in which fifty per cent of the hemoglobin is combined with oxygen and fifty with carbon monoxide If the atmosphere contains one-hundredth as much carbon monoxide as oxygen the equilibrium would be twenty-five per cent oxy-hemoglobin and seventy-five per cent carbon monoxide-hemoglobin. Thus if T_{o_2} and T_{co} are the pressures of oxygen and carbon monoxide and Hb_{o_2} and Hb_{co} the amounts of oxy and CO-hemoglobin in the blood the relations are expressed by the formula

$$\frac{T_{o_2}}{T_{co} \times 300 - Hb_{c_2}} \qquad Hb_{o_2}$$

The air in the lungs contains about 1500 parts of oxygen in 10,000. (It is actually somewhat less than fifteen per cent of oxygen. The affinity of hemoglobin for carbon monoxide may also be less or more than 300. We are here using round numbers merely to illustrate the principle without attempting mathematical precision.) We may calculate the blood equilibrium for any concentration of carbon monoxide in the air as shown in Table 1, and from these data we obtain the carbon monoxide dissociation curve of the blood as shown in Figure 1.

TABLE I

TO ILLUSTRATE THE BLOOD EQUILIBRIUM FOR VARIOUS ATMOSPHERES CONTAINING SMALL AMOUNTS OF CARBON MONOXIDE, WHEN THE AFFINITY IS 300

Oxygen in Lung Air		Affinity for Hemoglobin		Attractive Force	Carbon Monoxide		Affinity for Hemoglobin		Attractive Force	CO Attraction / Total Attraction		Saturation of Blood
Parts in 10,000					Parts in 10,000							CO per cent
1,500	X	1	=	1,500	1	X	300	= 300		300 / 1,500+300	=	16.6
1,500	X	1	=	1,500	2	X	300	= 600		600 / 1,500+600	=	28.5
1,500	X	1	=	1,500	3	X	300	= 900		900 / 1,500+900	=	37.4
1,500	X	1	=	1,500	4	X	300	= 1,200		1,200 / 1,500+1,200	=	44.4
1,500	X	1	=	1,500	5	X	300	= 1,500		1,500 / 1,500+1,500	=	50.0
1,500	X	1	=	1,500	6	X	300	= 1,800		1,800 / 1,500+1,800	=	54.5
1,500	X	1	=	1,500	7	X	300	= 2,100		2,100 / 1,500+2,100	=	58.3
1,500	X	1	=	1,500	8	X	300	= 2,400		2,400 / 1,500+2,400	=	61.5
1,500	X	1	=	1,500	9	X	300	= 2,700		2,700 / 1,500+2,700	=	64.3
1,500	X	1	=	1,500	10	X	300	= 3,000		3,000 / 1,500+3,000	=	66.6

The human body is an oxygen consuming engine. The oxygen is nearly all consumed in the tissues, chiefly the muscles. It is carried from the lungs to the tissues by the blood. Exposure to carbon monoxide causes loss of oxygen carrying power in the blood, as the right hand column of the table shows, from 16.6 per cent in an atmosphere of one part of the gas up to 66.6 per cent in ten parts.

These degrees of saturation — if we calculate merely on a rate of absorption of carbon monoxide equivalent to 0.1 per cent of the oxygen capacity of the blood per minute and per part of carbon monoxide in the air, as given above — would be reached in 166 minutes when air containing one part of the gas is breathed, and in 66.6 minutes with air containing ten parts of carbon monoxide. But this is by no means the case; for the more carbon monoxide the blood absorbs, the greater becomes the force with which this gas tends to diffuse out again into the air. The more nearly

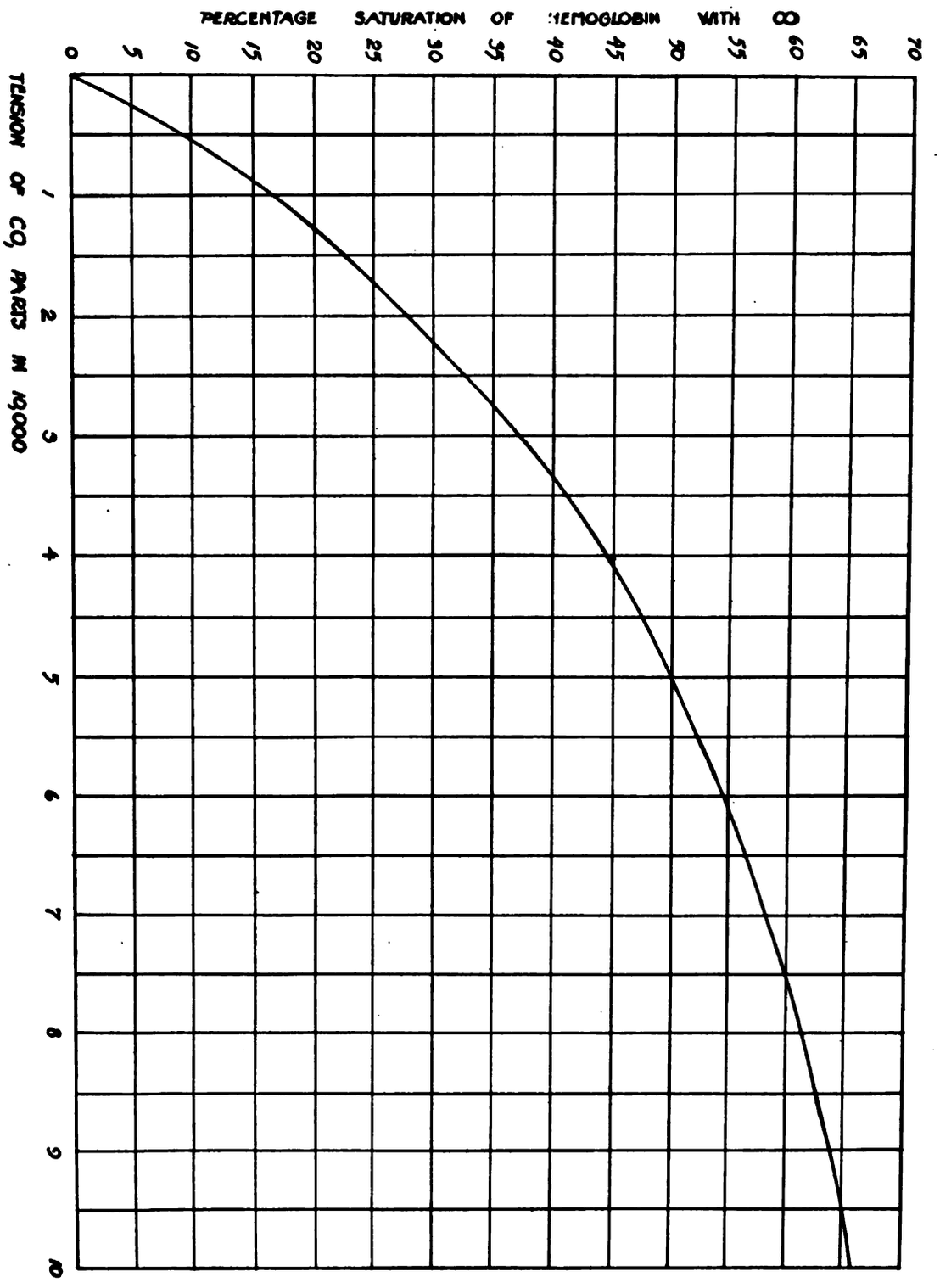

PERCENTAGE SATURATION OF HEMOGLOBIN WITH CO
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TENSION OF CO2 PARTS IN 10000
1
2
3
4
5
6
7
8
9
10

Figure I

this tendency equals and counterbalances the pressure of the gaseous carbon monoxide in the lungs, the slower the absorption of more carbon monoxide becomes. Thus to attain a condition of complete blood equilibrium not merely the times instanced above (166 and 66.6 minutes), but many hours would be actually required. Indeed the time is indeterminate. Doubtless other factors also play a part in slowing and stopping absorption.

It appeared to us, however, that a definite quantity for determination would be the time required for attainment of a percentage saturation of one-half the equilibrium values. Thus in an atmosphere containing two parts of carbon monoxide, for which the blood equilibrium is (Table 1) about twenty-eight per cent, how long a time would be required for the blood to become fourteen per cent saturated? How long in four parts, with an equilibrium value of forty-four, to attain twenty-two per cent saturation? Or with six parts and an equilibrium of fifty-four to reach twenty-seven per cent?

The answer to this question is the principal practical contribution to knowledge which we have to make. It is that the time for attainment of half equilibrium for persons sitting at rest and breathing concentrations of carbon monoxide up to seven parts is never considerably less than one hour.

The fact is of fundamental importance, we believe, for ventilation engineering. We have established it purely experimentally. It might easily be correlated with the oxygen consumption and the carbon dioxide elimination, but we have not thought this to be of practical importance to the immediate object of this report. It does not and it does not aim to, express what the average person does under the conditions; for many of our subjects fell much below this rate of absorption. The value of the rule is that it expresses the worst attainable, or so to speak, the " maximum load."

We may here conveniently consider the question often raised, of possible extreme individual susceptibility. It might conceivably arise from (1) anemia, that is a subnormal amount of hemoglobin; (2) from an unusual avidity of the individual's hemoglobin for carbon monoxide; (3) from unusual susceptibility to the ill effects of oxygen deficiency; or (4) from a volume of breathing much above the ordinary.

(1) The first is unimportant practically. Anemics need not spend long periods in ill ventilated garages, nor ride through tunnels on slow moving trucks. If, however, they are transported at the speed of a passenger car or an ambulance, through a two mile tunnel containing the average concentration of carbon monoxide here to be proposed, the time of exposure will be too brief to allow an absorption sufficient for any considerable ill effect.

(2) The second possibility has been investigated by us (see Section X), but not found to occur.

(3) There is reason to believe that there are individual differences in the degree of the ill effects induced by considerable oxygen deficiency. Aviators and mountain climbers exhibit such differences; and in our more extreme test, headache has occurred in some individuals, at a somewhat less percentage saturation of the blood than in others. We have, however, found no one who experienced this effect, the first sign of oxgyen deficiency, under the conditions of the standards which we shall propose.

(4) The volume of breathing is by far the most important element in rate of absorption of carbon monoxide, and thus in the individual variations in the ill effects of inhalation of this gas.

In general, the expired air of a healthy man contains four or five per cent of an atmosphere less oxygen than the inspired air; and this percentage deficit is nearly the same during rest with a breathing of eight liters, and under physical exertion with a respiration several times as large. In other words, the volume of breathing is roughly proportional to the amount of the oxidation and energy liberation occurring in the body. In our observations persons of vigorous physique and large breathing rates have absorbed carbon monoxide much more rapidly, as measured in per cent blood saturation, than those of more sedentary habit and delicate physique. As the standard which we shall propose is one adjusted to protect even the strong it will therefore afford an extra safeguard to the weak and sick, who breathe little (except in febrile cases) would absorb carbon monoxide comparatively slowly.

Only the case of children, whose active vitality involves a relatively large food and oxygen consumption and a corresponding volume of breathing, will this rule probably not hold, but even for the most active child a period of exposure of only ten or fifteen minutes to the concentration of carbon monoxide here approved will not be long enough for any considerable absorption of the gas.

The particular problem before us — that of a standard for the ventilation of the proposed vehicular tunnels under the Hudson River — may therefore be thus simply expressed: What percentage saturations of the blood with carbon monoxide cause appreciable discomfort in healthy men sitting at rest, and what do not? In view of the foregoing discussion, it is, we trust, clear that standards of concentration which will adequately protect men exposed for the greater part of an hour, will afford an enormous factor of safety for persons inhaling the vitiated air for only ten or fifteen minutes. We are informed by the engineers that all traffic through the tunnels will be in two distinct classes, namely: passenger cars which will make the trip in ten or twelve minutes and trucks which will take thirty-five or forty minutes.

The standards which we set ourselves to work out are such as will afford not only absolute safety, but also complete freedom from any trace of discomfort for healthy and vigorous adults exposed for periods of forty-five to sixty minutes.

Figure I. The carbon monoxide-hemoglobin curve of a blood having an oxygen: carbon monoxide affinity ratio of 1 : 300, showing the blood in equilibrium with various tensions of carbon monoxide, expressed as parts in 10,000 in the presence of 1500 parts of an atmosphere, of oxygen.

Figure II. Six cubic meter chamber and apparatus for introducing measured amounts of carbon monoxide. This chamber consists of a wooden framework covered with sheet iron. It contains a chair, table, and electric fan. It can be hermetically sealed by applying long and broad strips of adhesive plaster over the crevices between the door and chamber walls. The hand hole in the door is also sealed by plaster. Thru this hole the subject may thrust his hand when samples of blood are required for analysis.

With the diffusion fan running, measured quantities of water are introduced into the funnel. By opening the pinch clamps carbon monoxide is displaced from the bottle into the chamber. Samples of air for analysis may be withdrawn from the chamber by means of sampling tube. A rubber bag allows for expansion or contraction of the chamber air with changes of temperature.

Figure III. Six cubic meter chamber and apparatus for introducing measured amounts of carbon monoxide. Description under Figure II.

Figure IV. Apparatus for analysis of carbon monoxide by combustion. With cock (A) open, the burette (B) is filled with water by raising bottle (C); the cock (A) is then closed. A rubber bag containing the air to be analyzed is connected at (A). The cock is opened and a sample of air is drawn into the burette, and the cock closed.

The temperature of the water bath (D) is now equalized by blowing thru tube (E). The volume of the sample is determined at atmospheric pressure as follows: Bottle (C) is raised until the level of the water coincides with the level of fluid in the temperature control bulb (F) and the sliding marker X is adjusted to that level. Bottle (C) is now brought to such a height that the fluid levels in it and in the graduated tube of the burette are the same and a reading is taken. Cock (G) is opened, and by raising and lowering bottle (C) the air is displaced several times into the NaOH solution in bell (E); and the carbon dioxide is thus absorbed. Bottle (C) is then lowered until the level of the NaOH solution returns to the fixed mark Y on the stem of the bell (H). After again equalizing the temperature of the water bath (D) a second reading is taken. If the temperature of the sample has changed it will be found that when the fluid in bulb (F) is brought to the level of the mark X, the level of the fluid in the bottle (C) will be somewhat higher or lower. The difference in the levels is read off the scale on bottle (C) and the same difference of levels applied in reading the volume of the sample in burette (B).

The difference between the first and second readings divided by the first reading will give the percentage of carbon monoxide in the sample.

To determine the percentage of carbon monoxide, cock (G) is again opened and the sample displaced into bell (H). The platinum spiral, now above the level of the NaOH solution, is heated to a cherry glow by closing electric switch and the carbon monoxide oxidized to carbon dioxide. After combustion is complete the air is transferred from burette (B) to bell (H) several times until all the carbon dioxide is absorbed and the level of the NaOH solution is then brought to mark Y. Cock (G) is then closed. Having equalized the temperature in water bath (D), a third r ading is taken in the manner previously described. The difference between the second and third readings divided by the first reading (original volume of the sample) will give a figure a half greater than the percentage of carbon monoxide, since $2\ CO + O_2 = 2\ CO_2$, which CO_2 is absorbed by the NaOH solution. The actual percentage of carbon monoxide is therefore obtained by multiplying the decrease of column by two-thirds.

Figure V. Curves of elimination of carbon monoxide from the blood and pulmonary air after coming out of atmospheres containing various concentrations of carbon monoxide. Solid lines are the percentage saturation of the blood and dotted lines the tension of carbon monoxide in the pulmonary air.

Figure VI. Curves showing rate of absorption of carbon by the blood of persons exposed to concentrations up to seven parts of carbon monoxide in 10,000 of air, for periods up to one hour, during rest (sitting), and for shorter periods of walking and working. For discussion see text.

Figure VI-A. Illustration of method for applying absorption curve data to specific conditions arising in a vehicular tunnel. Longitudinal ventilation. Subject in a sitting position traveling in direction of air current. Duration of passage thru tunnel thirty-five minutes. The altitude of the triangles express the increments of saturation of the subject's blood while passing thru atmospheres increasing progressively in their carbon monoxide content. Effluent air equals seven parts carbon monoxide in 10,000 of air.

Figure VI-B. Illustration of method for applying absorption curve data to specific conditions arising in a vehicular tunnel. Longitudinal ventilation. Subject traveling against air current. Duration of passage thru tunnel thirty minutes. The altitude of the triangles express the increments of saturation of the subject's blood while passing from effluent air containing seven parts of carbon monoxide in 10,000 thru atmospheres decreasing progressively in their carbon monoxide content.

Figure VI-C. Illustration of method for applying absorption curve data to specific conditions arising in a vehicular tunnel. Longitudinal ventilation. Subject walking in direction of air current. The altitude of the triangle as under Figure VI-A.

Figure VI-D. Illustration of method for applying absorption curve data to specific conditions arising in a vehicular tunnel. Distributed ventilation. Subject in a sitting position traveling from A to E. Duration of passage thru tunnel sixty minutes. The dots indicate the percentage saturation of the subject's blood at various stages of the passage. The letters A, B, D, and E indicate the percentage saturation of the blood when the corresponding points in the tunnel are passed.

Figure VII. Apparatus in large gassing chamber for producing various concentrations of exhaust gas under conditions simulating those in a vehicular tunnel.

The apparatus was housed in a brick walled chamber of 12,000 cubic feet capacity.

A Ford car supported on jacks, A, A, A, A, with its rear wheels in apposition to pulleys B, B, rotates the dispersing fans, C, C, to insure the rapid dispersion of the exhaust gas in the chamber air. When the car is stopped, the fan shaft may also be turned by an electric motor (D).

The concentration of gas in the chamber is regulated by the valves on the exhaust. With one valve open, and the other closed all of the exhaust gas is discharged outdoors. By adjustment of the valves, any fraction of the exhaust gas is passed thru a pressure equalizer, and motor, and is discharged in proximity to one of the fans, After the desired concentration of exhaust gas is attained all the gas is discharged outdoors. An Orsat analyzer permits the analysis of the exhaust gas in course of the experiment. The efficiency of the engine cooling system is maintained by the water circulation (J).

Figure VIII. Apparatus in large gassing chamber for producing various concentrations of exhaust gas under conditions simulating those in a vehicular tunnel. Description under Figure VII.

Figure IX. Apparatus for determining the effects of various tensions of gasoline vapor on animals.

The blower drives room air thru a flask into which gasoline is supplied by way of a funnel. The flask is heated by an electric plate to accelerate vaporization of the gasoline. The air partially saturated with gasoline, passes thru the outlet at the top of the chamber. The concentration of vapor is regulated by the rate of the flow of gasoline from the funnel. At intervals samples of air from the animal chamber are drawn into the burette of the analyzer and the concentration of gasoline determined by absorption of the vapor with mineral oil. The oxygen in the air is determined, as an analytical check by means of phosphorus.

Figure X. Showing the effects of various tensions of gasoline vapor on animals. It will be noted that (unlike) carbon monoxide the physiological effects depend on the concentration of the vapor and bear no relation to the time of exposure.

Figure XI. Apparatus for collection of pulmonary air. With lungs fully inflated the subject expired into the flask and bag. The air is reinspired and the procedure repeated five times, ending with deep expiration. The clip at the mouth is then closed. After allowing the air in the apparatus to fall to room temperature, the other clip and clamp are closed. The air in the flask is analyzed for carbon monoxide by the Haldane method, and the contents of the bag by the iodine pentoxide methods.

Figure XII. Dissociation curve of carbon monoxide — hemoglobin in the presence of various concentrations of carbon monoxide in hydrogen. (After Haldane and Douglas.)

Figure XIII. Dissociation curves of carbon monoxide — hemoglobin in the presence of air — (oxygen at twenty-one per cent of an atmosphere). Curves A — (After Haldane and Douglas). Blood of two individuals equilibrated at thirty-eight degrees C, in vitro with various concentrations of carbon monoxide in atmospheric air. Curves B — Variations in the carbon monoxide dissociation curves of the blood from eighteen individuals examined by us (see Table IV). The bloods were equilibrated at twenty degrees C with various concentrations of carbon monoxide in atmospheric air. It will be noted that the affinity of carbon monoxide for hemoglobin increases inversely as the temperature.

Figure XIV. Dissociation curves from eighteen individuals in whom the hemoglobin varied from thirty-five to 110 per cent (mean normal 100). Blood equilibrated in vitro at twenty degrees C with various tensions of carbon monoxide in atmospheric air. The numbers at the right of the figure refer to the curve number of individuals' blood given in Table IV. The relative thickness of the curves is proportional to the number of bloods having the same carbon monoxide + oxygen affinity.

Figure XV. (After Haldane.) Showing the effect of temperature on the affinity of carbon monoxide for hemoglobin. Dissociation curves of carbon monoxide-hemoglobin from blood of the same individual when the blood is equilibrated in vitro at eleven degrees C, twenty-four degrees C and thirty-eight degrees C with various tensions of carbon monoxide in atmospheric air.

Figure XVI. (After Haldane and Douglas.) Curves showing the influence of charges in oxygen tension on the affinity of hemoglobin for carbon monoxide. Blood equilibrated in vitro at thirty-eight degrees C.

Figure XVII. (After Haldane and Douglas.) Dissociation curves of carbon monoxide in the presence of various tensions of carbon monoxide and in the absence of oxygen. Blood equilibrated in vitro at thirty-eight degrees C in mixtures of carbon monoxide, carbon dioxide, and hydrogen.

Figure XVIII. Apparatus for equilibration of blood solutions with carbon monoxide-air mixtures. The flasks containing the blood are held at the periphery of the turn table by adjustable collars. Thirty samples of blood can be rotated at one time. The flow of the blood film is regulated by modifying the speed of rotation and the inclination of the turn table. The latter is adjusted by a sliding block.

Figure XIX. Showing apparatus for determination of carbon monoxide by means of iodine pentoxide.

Figure XX. Apparatus for determination of carbon monoxide by means of iodine pentoxide.

EXPERIMENTS ON MEN IN SIX CUBIC METER CHAMBER

The method of studying the effects of various concentrations of carbon monoxide upon which we have chiefly relied for establishing our standard is illustrated in Figures II and III. It involves a chamber of six and four-tenths cubic meters, or 226 cubic feet, capacity.

The walls and door of the chamber are covered with galvanized sheet iron with soldered joints. The door is easily made gas tight by long strips of broad (two inch) adhesive plaster over the cracks along lintel, jambs and sill. The chamber holds any concentration of gas for a day without any appreciable loss from diffusion through undiscovered leaks. A small hole in the door allows the hand of the subject to be thrust outside for the withdrawal of blood. The hole is covered by a piece of adhesive plaster.

Into this chamber are introduced measured amounts of pure carbon monoxide. The gas is made by dripping formic acid into strong sulphuric acid and distilling by gentle heat into a large bottle filled with water which the gas displaces. The concentration of gas desired in the chamber is obtained by running into the bottle 640 c.c. of water per part of carbon monoxide desired, and thus displacing this volume of gas from the bottle through a tube into the chamber. An electric fan in the chamber insures immediate and complete mixing.

Two checks on the concentration of gas in the chamber were obtained. (1) By analysis of the carbon monoxide, before it was introduced, by a modified Orsat apparatus, and ignition with an electrically heated platinum spiral (See Figure IV), and (2) by analysis of a mixed sample of the air from the chamber by the iodine pentoxide method, or by means of diluted blood.

In this chamber in turn the members of the staff of this investigation and a few other persons, spent periods of one hour after amounts of carbon monoxide from two to eight, and in one case ten, parts had been introduced. While they sat and read most of the time, there were a sufficient number of acts — such as turning on the electric fan, standing up to look out of the window for a moment, opening and closing flasks to take air samples for later analysis, et cetera — to correspond fairly well with the activity of the driver of a car. When we speak of the absorption of carbon monoxide by a person " sitting at rest " the condition must be understood as only such moderate rest as this.

Blood, to the amount of twenty or thirty drops, was drawn from a finger before the subject entered the chamber; and .02 c.c. were drawn at the middle of the period and at the end and usually once or twice during the next three hours. These bloods were analyzed for carbon monoxide by the carmine method (described in Section IX).

After the subject had been out of the chamber for a few minutes the tension of carbon monoxide in his lungs, supposedly in equilibrium with the blood, was determined by breathing back and forth several times, during twenty to thirty seconds, into a rubber bag. Foot ball or basket ball " bladders " were used for this purpose. (A series of check determinations on four subjects showed that the maximum concentration of CO from these bags was reached in five rebreathings during thirty seconds.) This air was analyzed for carbon monoxide by the iodine pentoxide method (See Section XI), or by the blood carmine method (Section IX).

The subject's volume of resting breathing was determined either in or outside of the chamber by means of a mouthpiece, nose clip, double valves, and Douglas bat and gas meter; and the volume per minute was calculated.

In some experiments the respiration was increased by exercise and the increase was measured, and correlated with the correspondingly greater absorption of carbon monoxide. In these experiments the subject did " stationary " walking, or running, in the chamber by lifting the feet and stamping. The exertion involved is considerable, but with care it can be kept quite uniform for half an hour at a time.

The pulse was counted in the chamber, and before and after the test.

The effect of running up and down four flights of stairs, each twelve feet vertically, on the pulse and respiration was also determined before and after the period in the chamber.

In a few cases the retinal fields were determined and plotted. The results were that, with the degrees of anoxomia occurring in these experiments, the effects on vision in this respect were unimportant.

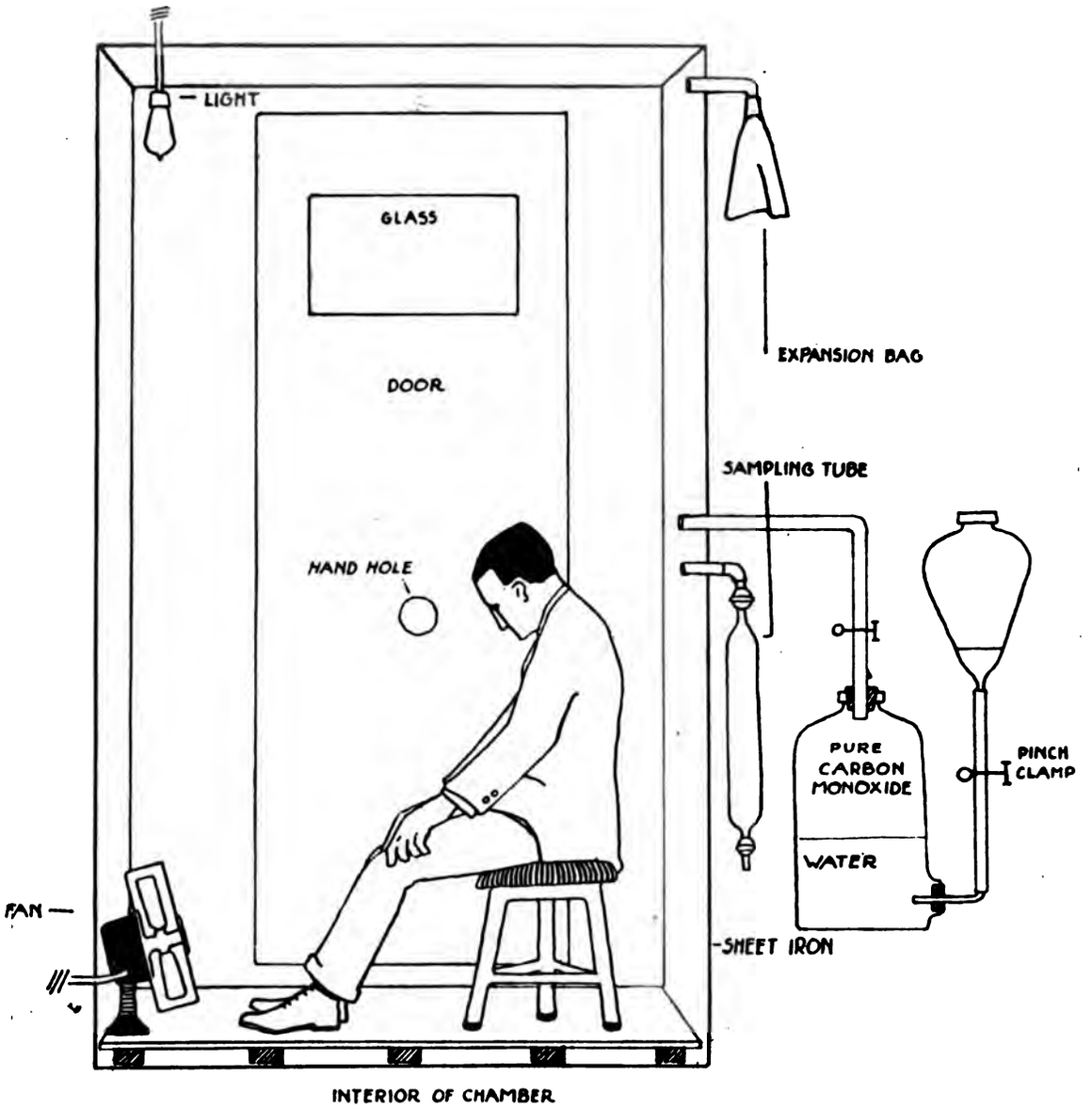


Figure II

The Romberg test, the ability to stand erect with eyes closed without wavering, was also used after the period in the chamber. In some cases, after an hour in eight parts, it showed marked loss of equilbrium.

But of all signs and tests, both in the experiments in the small chamber here under discussion, and in those that are to be described in the next section, the typical carbon monoxide, or oxygen

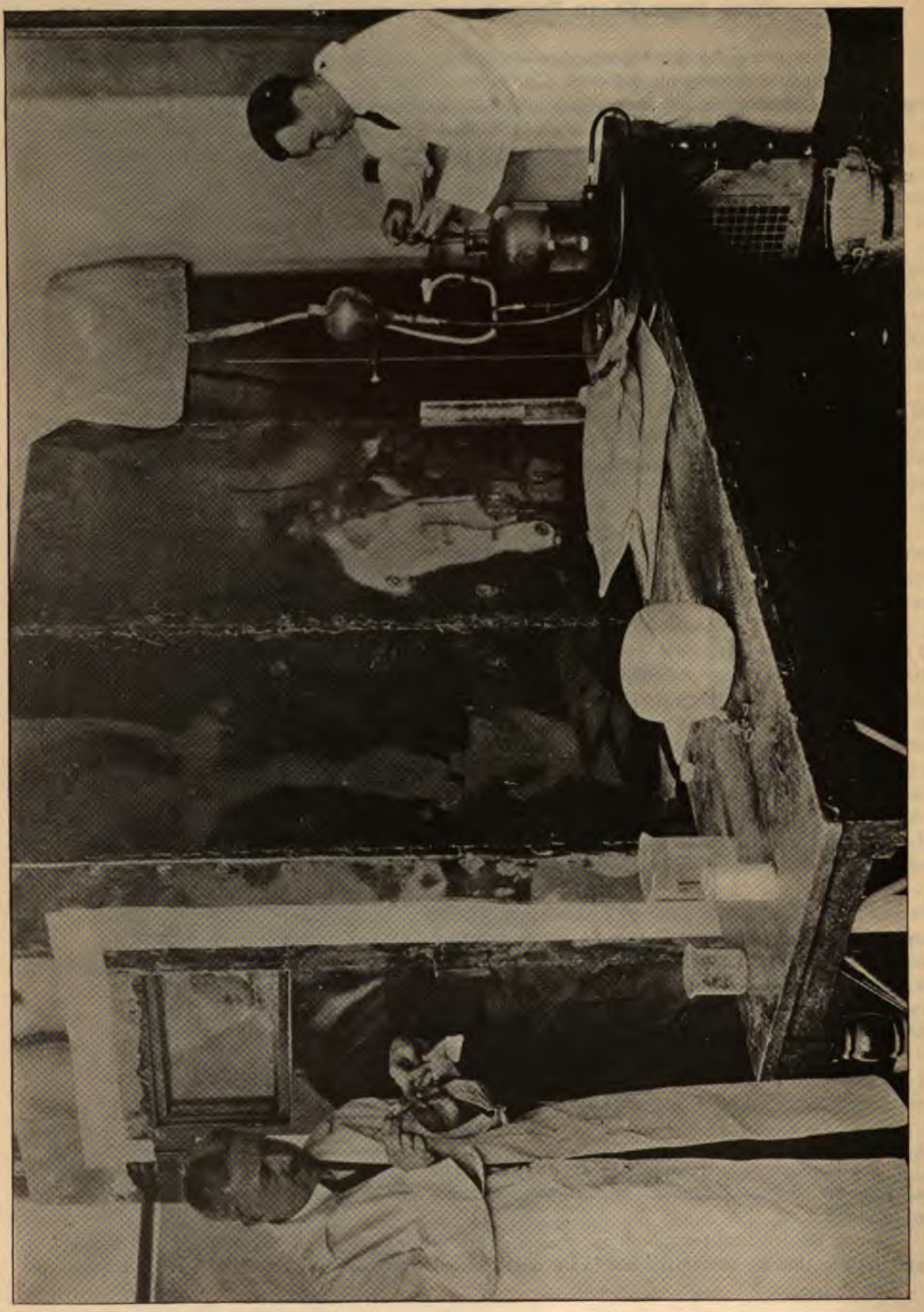


Figure III

deficiency, headache proved most definite and reliable. It is a distinctly localized pain, usually frontal, throbbing, intensified by lying down or by exertion. It is sometimes accompanied by more or less nausea, readily increasing to vomiting. The mind is not clear, except with an effort. One's surroundings seem a little strange. The temper is easily upset, very much as in alcoholic intoxication, and the judgment is liable to be bad.

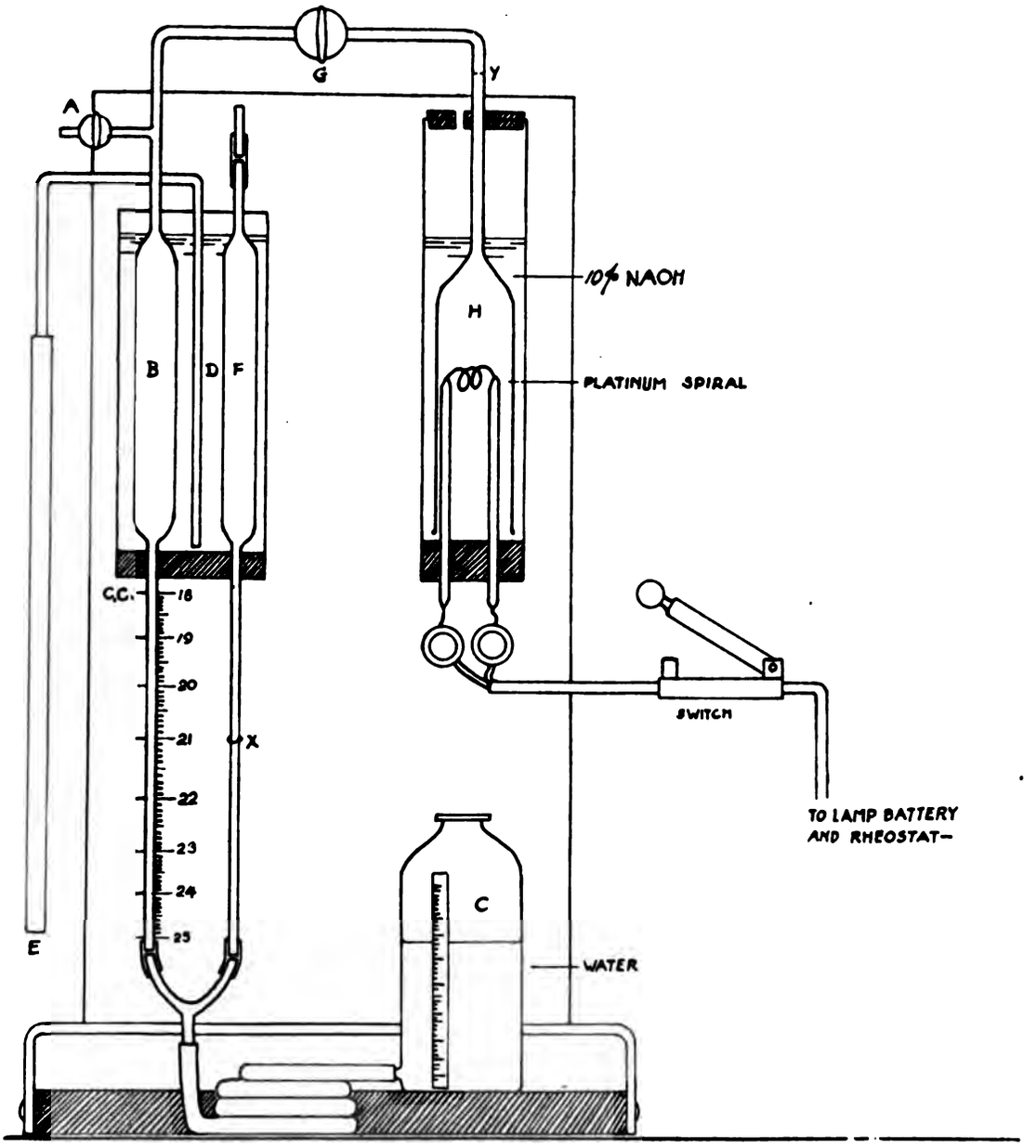


Figure IV

There are wide variations in the degree of this headache and in the experiments discussed in this section it was never extreme. On the border line it verged merely into slight lassitude. As a criterion of the effects of carbon monoxide, however, it is more distinct than any artificial test. Concentrations of gas too weak and periods of exposure too short to induce this sign in any one may be considered entirely harmless.

The data of thirty-nine experiments on nine men and one woman done in this way are given in Table II and are summarized in Table III.

From Table III it appears that no one had an appreciable degree of headache after a period of one hour in the chamber with four parts of carbon monoxide or less. With six parts the degree of

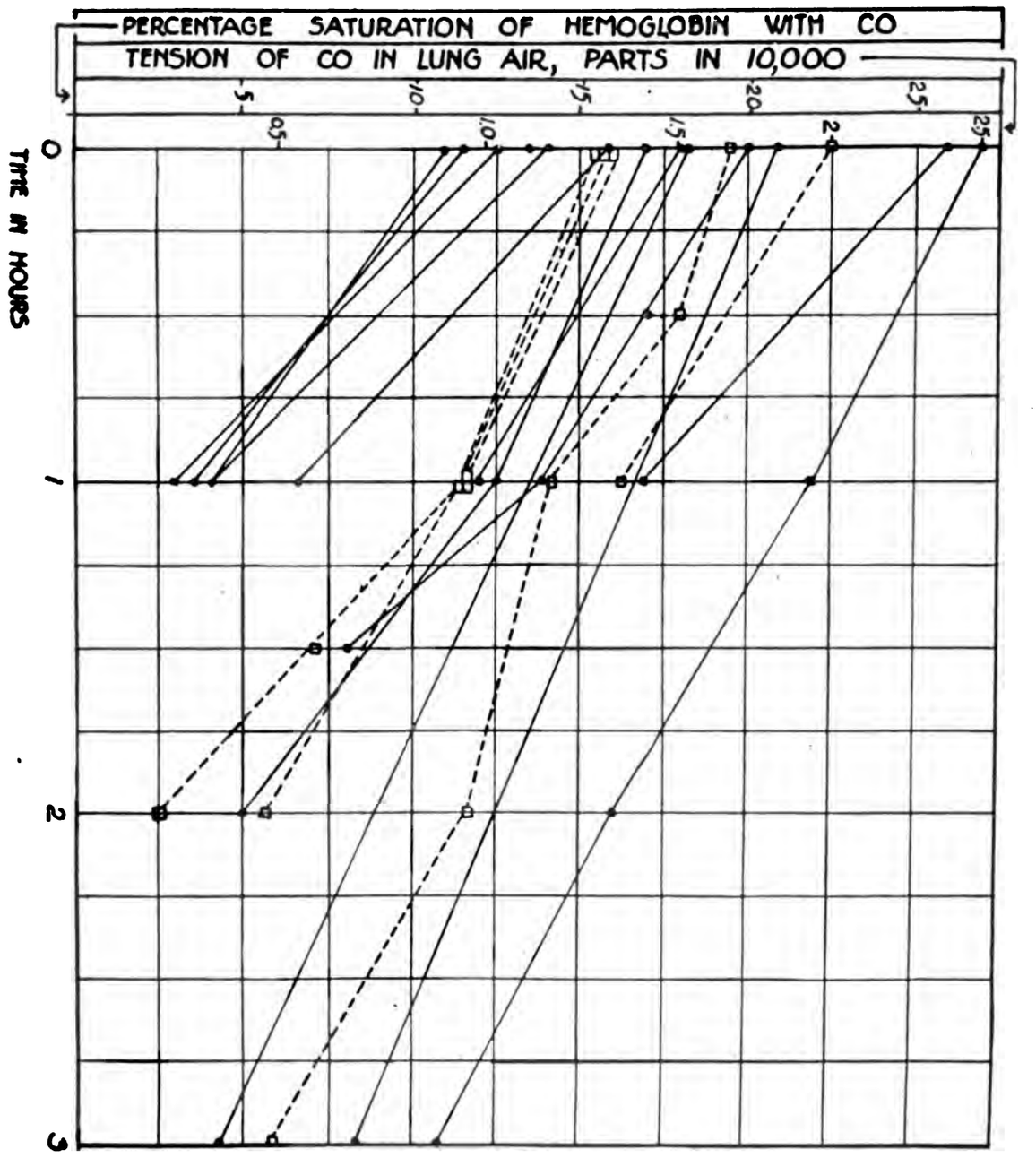


Figure V

effect if any was usually very slight. With eight parts there was decided discomfort for some hours, altho not enough to interfere with efficient work in the laboratory or at the desk. After an hour in ten parts even an unusually resistant subject was rather miserable and averse to work

for five or six hours and could still recognize the effects after twelve hours. Examination of these tables enables us to reach a working rule regarding the rate of absorption of carbon monoxide. For in Table III we find that up to and including concentrations of six parts of carbon monoxide in ten thousand of air the figures in column three do not exceed values of about one-half those in column two. In other words, during one hour sitting at rest in such atmospheres a man's blood never absorbs considerably more than half the amount of carbon monoxide which it would take up if he stayed in the atmosphere indefinitely. Inactive and small breathing persons absorb less. At concentrations of eight and ten parts of carbon monoxide the figures deviate slightly from this rule. But the rule of half saturation appears to be safe and convenient up to seven.

It appears further that a man who exercises sufficiently to double the volume of breathing absorbs as much carbon monoxide in half an hour as he does at rest in one hour. We have found in other experiments, which need not be given here in detail, that a man walking fast breathes about twice as much air as when sitting still, and that a man hurrying, or doing rather heavy manual labor breathes about threefold, and under exertion even more; these figures may be directly applied to conditions as they occur in regard to absorption of carbon monoxide, and the estimation of the time required for half equilibrium may be shortened accordingly.

As regards the elimination of carbon monoxide from the blood after gassing, the data in columns 9, 10 and 11 in Table II, show that the process is not complete until one or two hours after return to fresh air, or even longer. Roughly the rate of elimination is thirty to fifty per cent per hour, depending, doubtless, on bodily activity and the volume of fresh air breathed. This evidence is summarized in Figure VI.

TABLE III

SUMMARIZING RESULTS OF EXPERIMENTS (TABLE II) IN SIX CUBIC METER CHAMBER

CONCENTRATION OF CO IN AIR BREATHED	Corresponding Equilibrium value for the Blood	FOUND AFTER ONE HOUR		
		In the Blood	In the Pulmonary Air	Headache
Parts in 10,000	Percentage Saturation	Percentage Saturation	Parts in 10,000	
2	23	11–12	.....	None
4	36	14–22	1.30–1.36	None
6	47	16–26	1.0–1.98	None or slight
8	53	26–34	1.7–2.3	Distinct
10	58	38	.....	Marked for several hours

III

THE RATE OF ABSORPTION OF CARBON MONOXIDE AND STANDARDS OF ALLOWABLE VITIATION OF THE AIR

The essential practical results of the experiments in the six cubic meter chamber, and indeed of this entire investigation, are summed up in Figure VI. It shows the rate at which carbon monoxide may be absorbed and the amounts at which physiological effects may occur. It is based on the data in Tables II and III and is confirmed by the evidence obtained on a large number of people in the large gassing chamber to be presented in Section 7.

The curves are drawn to show the rate of absorption of carbon monoxide when air with various concentrations from one to seven parts of this gas in ten thousand is breathed. They express the absorption by the blood during one hour of one-half the amount of carbon monoxide that would be taken up after prolonged stay in each of these atmospheres.

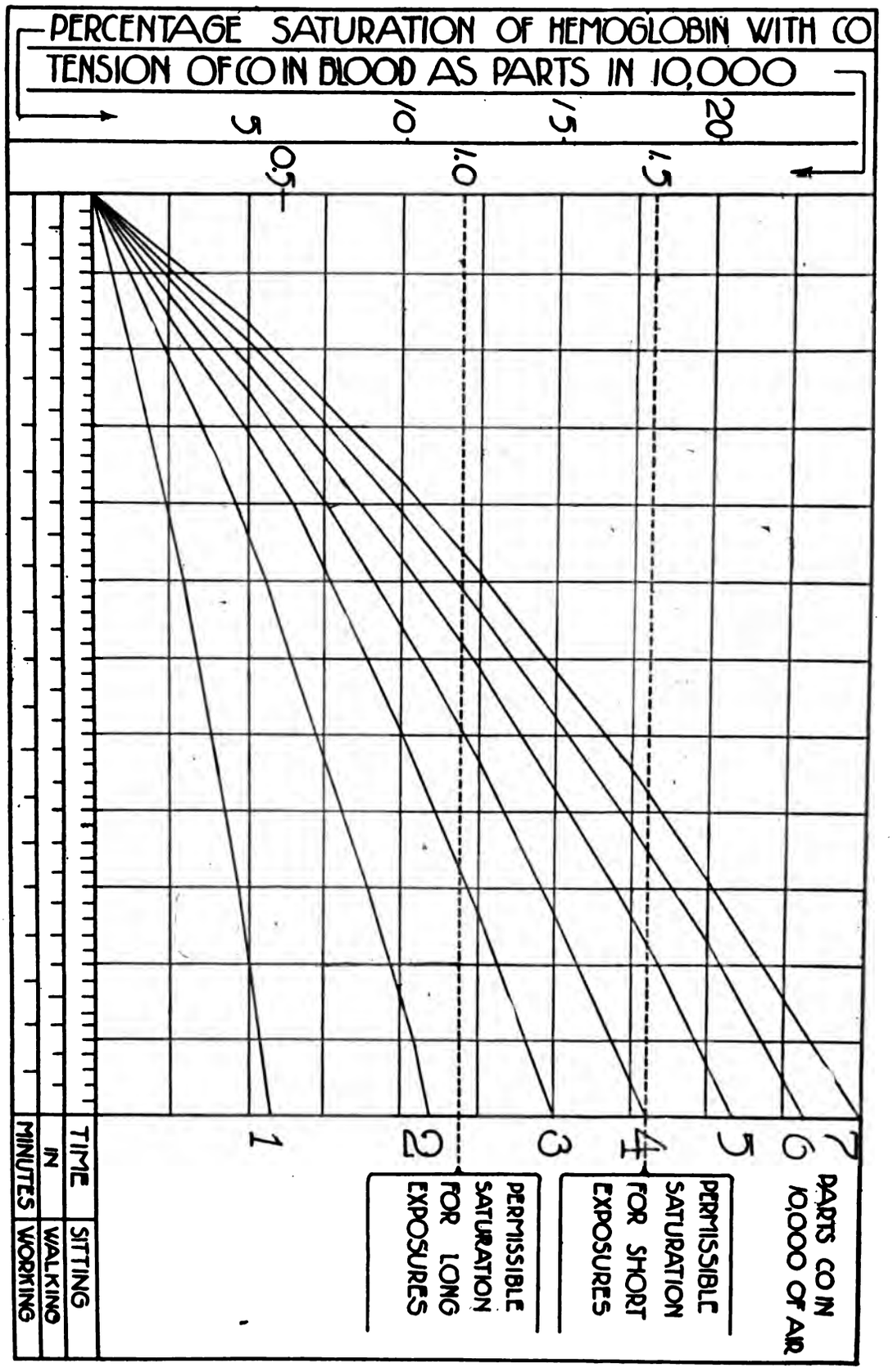

PERCENTAGE SATURATION OF HEMOGLOBIN WITH CO
TENSION OF CO IN BLOOD AS PARTS IN 10,000
20
15
10
5
1.5
1.0
0.5
1
2
3
4
5
6
7
PARTS CO IN 10,000 OF AIR
PERMISSIBLE SATURATION FOR SHORT EXPOSURES
PERMISSIBLE SATURATION FOR LONG EXPOSURES
TIME
IN
MINUTES
SITTING
WALKING
WORKING

Figure VI

One of the columns of figures at the left in this diagram expresses the percentage saturation attained by the blood. The other column shows the corresponding tension of carbon monoxide in the atmosphere in parts per ten thousand of air, with which the blood would be in gaseous equilibrium. In other words, the figures in column 2 indicate the amount of carbon monoxide that should be found in a pulmonary air sample, obtained by the method shown in Figure VI, when the blood in the lungs contains these percentages of carbon monoxide.

Below the base line the three lines of figures show respectively the (minimum) time required to reach these percentage saturations, when the subject is at rest, when he is walking at a moderate pace and breathing a double volume of air, and when he is sufficiently active to breathe threefold, — as a man at work may.

Horizontal dotted lines have been drawn at the levels of twelve and eighteen per cent blood saturation,— corresponding to tensions of one and one and four-tenths parts per ten thousand. The lower line indicates the amount of carbon monoxide which even after an exposure of several hours would not induce very disagreeable effects. The upper expresses the level above which in our experiments slight discomfort and headache have generally resulted after an exposure of one hour.

This diagram has a very wide application. One may take off from the curves, by means of a pair of dividers, the quantities of carbon which may be absorbed by a person passing through any variety of concentrations of carbon monoxide,— as may be the case in different parts of a tunnel. From the curves one sees at a glance that if the tunnel is ventilated transversely so as to contain everywhere four parts of carbon monoxide in ten thousand,— corresponding to 2500 cubic feet of fresh air per minute per cubic foot of carbon monoxide produced by cars,— a passage of three-quarters of an hour, the rate for slow trucks, would produce no appreciable discomfort. It is also evident when one plots the matter out — as has been done for the sake of illustration in Figures VI a, b, and c — that if the tunnel is ventilated longitudinally, and the effluent air contains six parts of carbon monoxide, the physiological effect will be at least as good as with a uniform concentration of four parts in ten thousand. In this case the ventilating fans need supply only ten thousand cubic feet of air for each six cubic feet of carbon monoxide thrown off by the cars in the tunnel, or 1666 cubic feet of fresh air per minute per cubic foot of carbon monoxide. This is true if the air is forced in at one end and out at the other. It is also true if the tunnel is ventilated in sections so that the air at some points contains only a trace of carbon monoxide and at others is contaminated progressively with from one to seven parts in ten thousand of air as would be the case for instance if fresh air was driven in at the middle and ends of the tunnel, and drawn out at the two intermediate points, e. g., air shafts at the pier heads on each side of the Hudson River. This is illustrated in Figure VI-d.

It is evident from the diagram that if at any point the concentration exceeds six parts of carbon monoxide in ten thousand of air, men doing hard work for even a short time will be unfavorably affected.

On the other hand, the curves show that passengers in cars going through the tunnel in ten or fifteen minutes will absorb very little carbon monoxide. This factor of safety is, we believe, sufficient to afford ample protection for children and invalids. The standard here proposed for exposures of forty-five minutes — four parts in ten thousand, or its equivalent in an average of concentrations from zero up to six in ten thousand — affords in the light of our experiments not only complete safety but also an assurance of freedom from disagreeable effects.

Risk of considerable discomfort would begin at eight to ten parts of carbon monoxide in ten thousand of air in periods of one hour during rest and for shorter periods during exertion. Actual danger would begin with concentrations not very much higher and periods not very much longer.

The point should be emphasized, however, that we are dealing only with a standard of chemical purity of the air. Other features of tunnel ventilation, for example, wind velocity, moisture, temperature, et cetera, are not included in, and comfort in these respects is not assured by, the standard here defined.

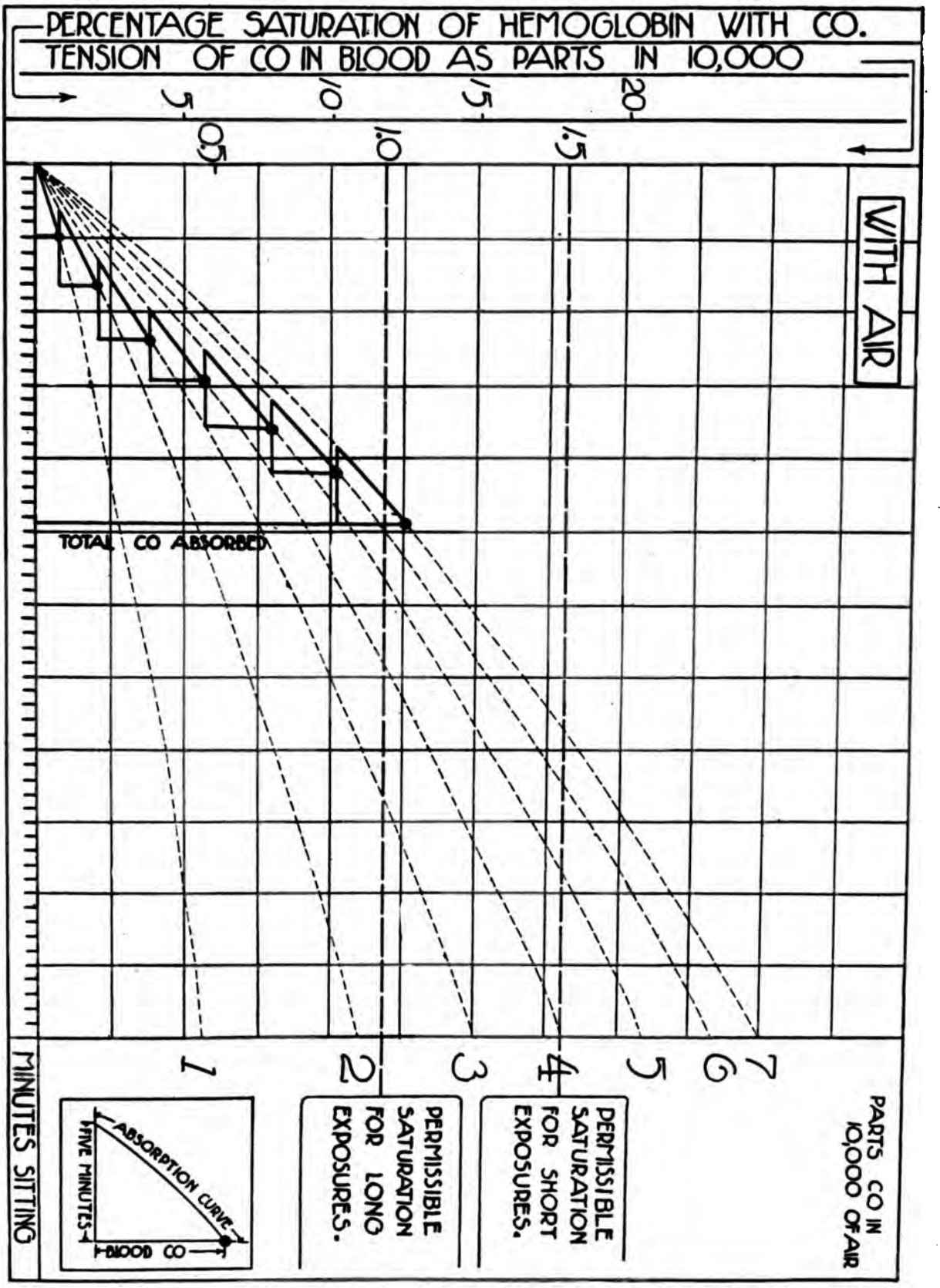

PERCENTAGE SATURATION OF HEMOGLOBIN WITH CO.
TENSION OF CO IN BLOOD AS PARTS IN 10,000
20
15
10
5
1.5
1.0
0.5
WITH AIR
TOTAL CO ABSORBED
MINUTES SITTING
1
2
3
4
5
6
7
PERMISSIBLE SATURATION FOR LONG EXPOSURES.
PERMISSIBLE SATURATION FOR SHORT EXPOSURES.
PARTS CO IN 10,000 OF AIR
ABSORPTION CURVE
FIVE MINUTES
BLOOD CO

Figure VI-a

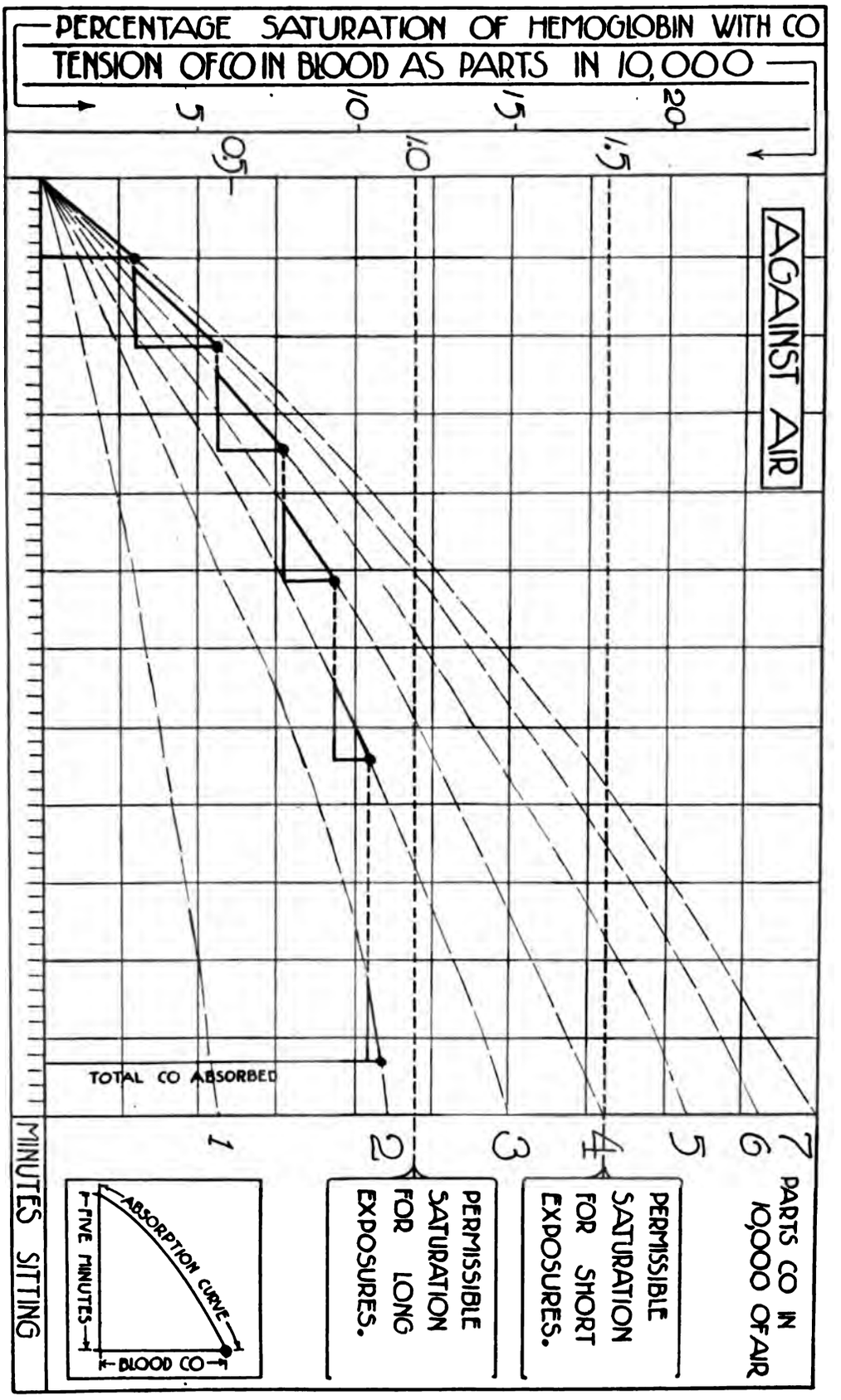

PERCENTAGE SATURATION OF HEMOGLOBIN WITH CO
TENSION OF CO IN BLOOD AS PARTS IN 10,000
5
10
15
20
0.5
1.0
1.5
AGAINST AIR
TOTAL CO ABSORBED
MINUTES SITTING
1
2
3
4
5
6
7
PARTS CO IN 10,000 OF AIR
PERMISSIBLE SATURATION FOR SHORT EXPOSURES.
PERMISSIBLE SATURATION FOR LONG EXPOSURES.
ABSORPTION CURVE
FIVE MINUTES
BLOOD CO

Figure VI-b

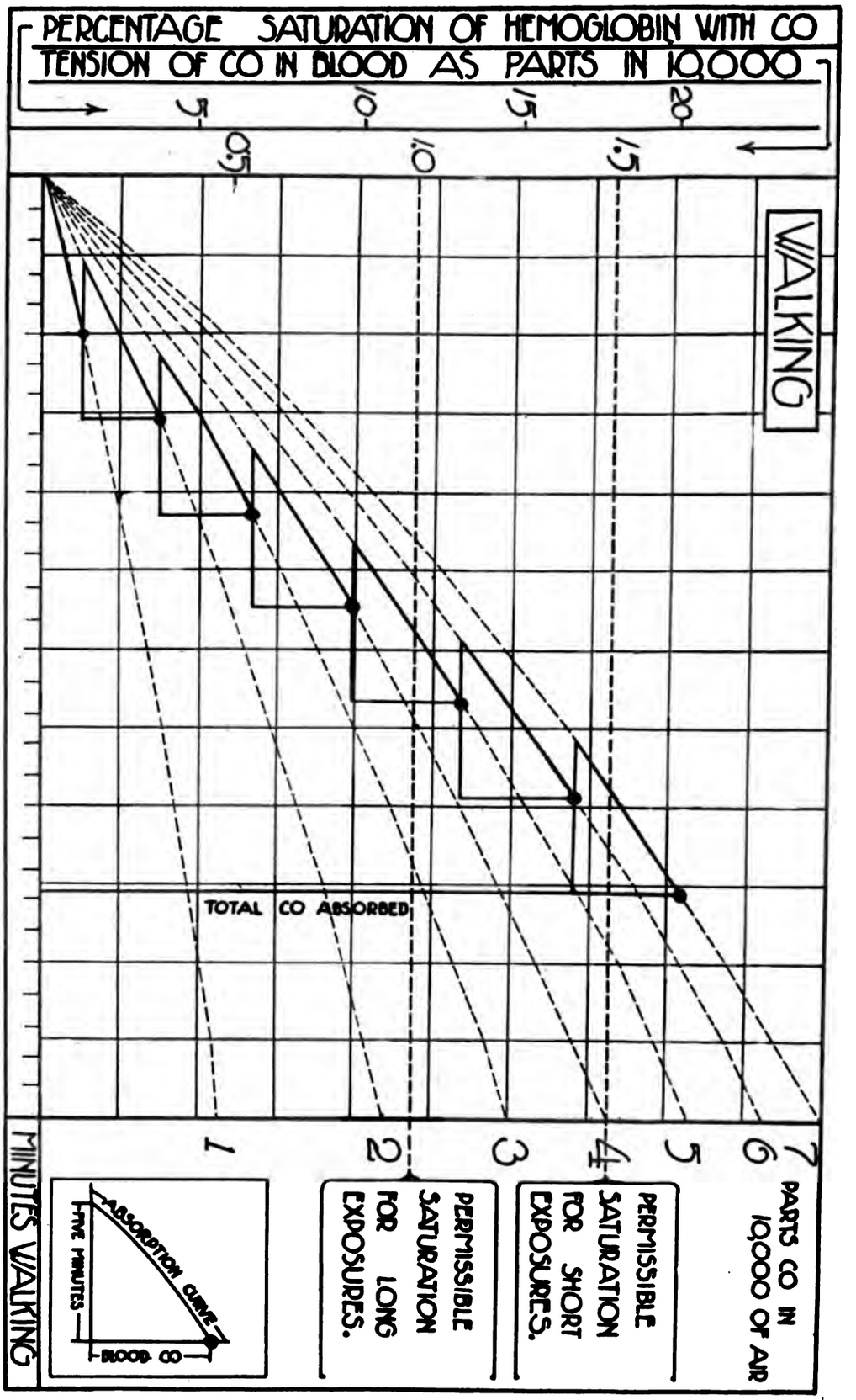

PERCENTAGE SATURATION OF HEMOGLOBIN WITH CO
TENSION OF CO IN BLOOD AS PARTS IN 10,000
WALKING
TOTAL CO ABSORBED
MINUTES WALKING
PERMISSIBLE SATURATION FOR SHORT EXPOSURES.
PERMISSIBLE SATURATION FOR LONG EXPOSURES.
PARTS CO IN 10,000 OF AIR
ABSORPTION CURVE
FIVE MINUTES
BLOOD

Figure VI-c

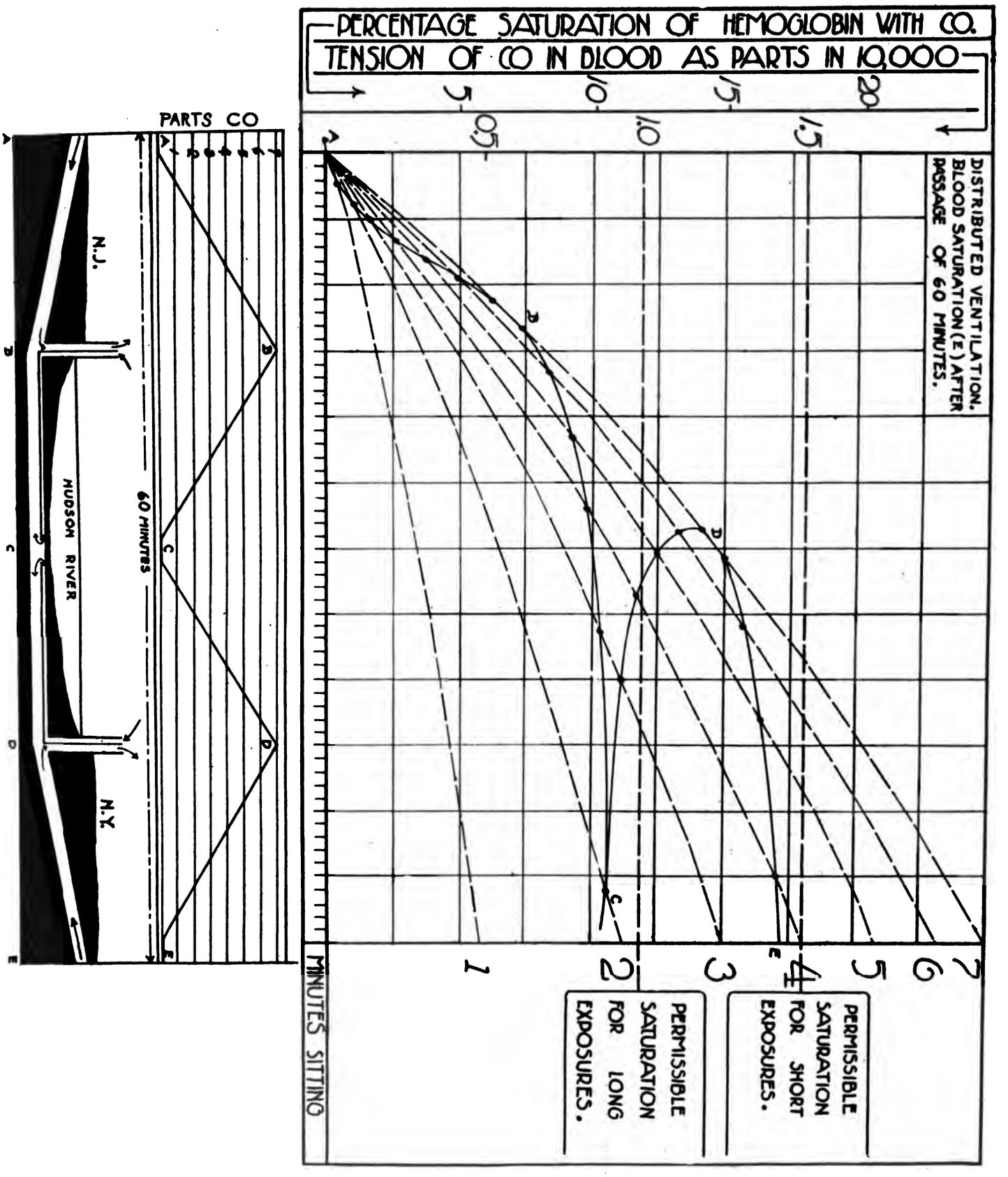

PERCENTAGE SATURATION OF HEMOGLOBIN WITH CO.
TENSION OF CO IN BLOOD AS PARTS IN 10,000
DISTRIBUTED VENTILATION. BLOOD SATURATION (E) AFTER PASSAGE OF 60 MINUTES.
PERMISSIBLE SATURATION FOR SHORT EXPOSURES.
PERMISSIBLE SATURATION FOR LONG EXPOSURES.
MINUTES SITTING
PARTS CO
N.J.
HUDSON RIVER
N.Y.
60 MINUTES

Figure VI-d

TABLE II

PHYSIOLOGICAL OBSERVATIONS ON MEN IN SIX CUBIC METER GASSING CHAMBER

SUBJECT	Date	Concentration of CO in air	Time of exposure	Remarks	Respiratory volume	Blood CO per cent		Alveolar air CO parts per 10,000	Time	After gassing, blood saturation	Alveolar air	Pulse				Symptoms
												Normal	During gassing		After gassing	
		Parts in 10,000	Min.		L. per Min.	30 min.	1 hour	1 hour	Min.	Per cent	Parts CO		30 min.	1 hour		
Y. Henderson	1/23/20	2	60	At rest	10	6.0	11	.....	65	4	.....	70	70	.....	70	None.
Y. Henderson	1/27/20	2	30	Exercising	26	12.5	.....	.....	60	3	.....	70	.....	.....	.....	None.
H. W. Haggard	1/27/20	2	60	At rest	12	.....	12	.....	60	3	.....	80	76	74	76	None.
M. C. Teague	1/29/20	3	60	At rest	14	.....	13	.....	.....	.....	.....	72	72	72	.....	None.
A. L. Prince	1/29/20	3	60	At rest	.....	.....	10	.....	.....	.....	.....	84	84	82	82	None.
H. W. Haggard	1/30/20	3	60	At rest	12	7.0	14	.....	60	4	.....	74	74	74	76	None.
Y. Henderson	1/30/20	4	30	Exercising	31	16.0	.....	.....	.....	.....	.....	.....	.....	.....	.....	None.
Y. Henderson	1/26/20	4	60	At rest	11	9.0	22	.....	150	5	.....	72	72	72	68	None even after exertion of cranking car.
Y. Henderson	1/19/20	4	60	At rest	10	.....	.....	.....	.....	.....	.....	.....	.....	72	77	None even after exertion of cranking car.
M. C. Teague	1/19/20	4	60	At rest	.....	.....	18	.....	180	4	.....	72	72	72	.....	None.
I. D. Ross	2/ 2/20	4	60	At rest	8	.....	17	.....	.....	.....	.....	74	70	74	76	None.
R. M. Wunderlich	2/11/20	4	60	At rest	.....	.....	.....	1.36	60 90 120	....	1.05 .62 .20	72	72	71	72	None.
F. Wentzel	2/12/20	4	60	At rest	9	.....	18	1.33	60	12	1.00					
W. B. Fulton	2/12/20	4	60	At rest	8	.....	17	1.30	60 120	12 5	1.10 .50	76	71	71	80	None.
A. L. Prince	1/27/20	4	60	At rest	.....	.....	14	.....	.....	.....	.....	.....	.....	.....	.....	None.
C. Rollands	2/ 2/20	4	60	At rest	7	.....	14	.....	30	17	.....	76	74	72	72	None.
H. W. Haggard	2/ 4/20	4	60	At rest	12	.....	20	.....	60 90	14 8	....	70 80	68 74	68 72	74 82	None. None.
H. W. Haggard	2/ 4/20	4	60	At rest	13	.....	21	.....	.....	.....	.....	.....	.....	.....	.....	None.
F. Wentzel	2/28/20	5	60	At rest	7	.....	.....	0.9	.....	.....	.....	.....	.....	.....	.....	None.
M. C. Teague	2/ 2/20	6	60	At rest	.....	.....	21	1.3	180	7.8	.....	72	72	68	72	Slight occipital headache persisting two hours, felt drowsy.
C. Rowlands	1/26/20	6	60	At rest	7	.....	16	1.26	25 180	....	1.12 .94	.....	.....	.....	.....	None.
A. L. Prince	2/ 5/20	6	60	At rest	.....	.....	16	.....	.....	.....	.....	74	74	72	74	None.
H. W. Haggard	2/ 9/20	6	60	At rest	11	.....	25	1.98	60	.....	1.42	80	76	76	82	Slight frontal headache lasting four to five hours.
Y. Henderson	1/28/20	6	60	At rest	13	13	26	.....	60	17.0	.....	72	68	68	.....	Very tired.
T. D. Ross	2/21/20	6	60	At rest	.....	.....	17	1.2	.....	.....	.....	.....	.....	.....	.....	None.
F. Wentzel	2/26/20	6	60	At rest	.....	.....	16	1.0	.....	.....	.....	.....	.....	.....	.....	None.

W. B. Fulton	2/26/20	6	60	At rest	9	.....	18	1.24	60	6.4	.....	74	68	68	72	None.
F. Wentzel	2/10/20	6	60	At rest	.....	.....	18	1.25	.....	.....	.....	78	74	76	74	None.
H. W. Haggard	2/29/20	6	15	Moderate activity	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	None.
H. W. Haggard	3/ 1/20	6	10	Moderate activity	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	None.
A. L. Prince	3/ 3/20	6	13	Moderate activity	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	None.
C. Rowlands	1/26/20	8	60	At rest	7	.....	34	2.3	.....	.....	.....	74	76	80	84	No definite symptoms though drowsy and uncomfortable.
M. C. Teague	2/18/20	8	60	At rest	.....	.....	32	2.3	.....	.....	.....	72	72	82	88	Decided headache and irritability, three to four hours.
O. Stockman	3/10/20	8	60	At rest	.....	.....	27.8	1.4	30 70 100 175 210 250	27.5 16.2 19.6 5.1 0.0 0.0	1.2 1.2 .7 .6 .4	76	76	78	80	Irritability and headache, four to eight hours.
H. W. Haggard	3/ 5/20	8	60	At rest	12	.....	34	.....	.....	.....	.....	74	78	78	84	Decided headache, very miserable eight hours, short of breath on exertion.
F. Wentzel	3/10/20	8	60	At rest	.....	.....	26	2.0	60	.....	1.4	.....	.....	.....	.....	Drowsy and uncomfortable for two hours.
H. W. Haggard	3/12/20	8	15	Moderate activity	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	None.
H. W. Haggard	2/19/20	9	60	At rest	10	.....	34	.....	.....	.....	.....	76	74	74	80	Decided frontal headache, irritable six hours.
Y. Henderson	1/20/20	10	60	At rest	13	27	38	.....	98	.....	.....	78	.....	90	90	Throbbing frontal headache, irritable at times; Cheyne-Stokes breathing.

IV

THE CONCORDANCE OF THE STANDARD HERE PROPOSED WITH THE OBSERVATIONS OF OTHER INVESTIGATORS

The standard defined in Figure VI may seem from the work of others, especially that of Haldane, unduly high, if one fixes attention upon the concentration of carbon monoxide in the air breathed; or it may appear unnecessarily low, if stated in terms of the maximum percentage saturation of the blood and the corresponding tension.

The work of Haldane is so preëminent in this field, alike in amount, thoroughness, and practicality, that discordance between the conclusions drawn from his investigations and the standard here proposed would require elaborate explanation and defence. In fact, however, we believe that when all aspects of the question are taken into consideration our observations and conclusions, although differing in detail, are essentially concordant with those of Haldane.

Briefly stated his principal conclusions were as follows:

The symptoms caused by carbon monoxide depend upon the extent to which the hemoglobin has been saturated. The symptoms are due solely to the deficiency of the oxygen percentage in the blood.

When the air containing carbon monoxide is breathed about half the carbon monoxide actually inhaled is absorbed except toward the end of the process when absorption is coming to a standstill.

The rate of absorption and time required for symptoms to appear is proportional to the respiratory exchange and may be very much shortened by the increased breathing of exercise.

The symptoms do not become appreciable during rest until the blood is about a third saturated. An individual in this condition suffers from palpitation and throbbing in the head and is liable to become faint or dizzy on any exertion, such as that of ascending a stair or on sudden exposure to cold air.

In experiments on himself Haldane found that, when fifty per cent saturated, he could scarcely stand and could not walk alone without falling down. There was giddiness, dullness of the senses and distinct shortness of breath and labored breathing.

In the course of two or three hours after leaving the contaminated air he found that nearly all the carbon monoxide disappears from the blood which has then returned to its normal condition. A headache lasting for some hours is likely to ensue from the exposure if the latter is sufficiently long.

In reporting on the conditions which should be maintained in the Underground Metropolitan Railways of London, he said, "Roughly speaking, the probable action on a healthy person of varying percentages of carbon monoxide in the air may be stated as follows: 2.5 volumes per 10,000 would suffice after a sufficient time (after an hour an a half during rest, but very much less during even slight exertion) to cause symptoms just distinctly appreciable on exertion. Five volumes per 10,000 would cause marked dizziness or fainting on exertion, nine volumes would cause inability to walk, and about fifteen volumes might produce death. Considering the enormous number of people in various states of health who use the railway, — it seems desirable that not more than one volume per ten thousand of this gas should be present in the air."

To these statements may be added the fact that Burrell found that after breathing air containing twenty-five parts of carbon monoxide per ten thousand of air for twenty minutes he had at first only a slight headache, but later became ill. The illness lasted for several hours and was accompanied by nausea and headache.

The agreement of these statements with our conclusions is sufficiently close to need no further discussion, until the question of allowable concentration of carbon monoxide — a concentration producing no appreciable effects in any one — is reached. On this point Haldane recommended one part in ten thousand while we approve concentrations up to four parts, or with longitudinal ventilation even six.

It is to be noted, however, that the conditions to which Haldane's recommendations applied were in some respects different from those which will occur in a vehicular tunnel. The motive power in the London Underground railways was at that time, 1897, furnished by steam engines burning coke. The engine drivers and train crews and even some passengers might be exposed for considerable periods — much longer than we have figured on. Haldane seems to have had in mind the possibility that exposure might be so long that the blood would come nearly into equilibrium with the tension of carbon monoxide in the air breathed and reach a corresponding percentage of saturation. We, on the contrary, are basing our estimates on times of exposure too short for the attainment of more than half the equilibrium degree of saturation.

The apparent discrepancy between the two standards lies in the figures for the concentration of carbon monoxide in the air breathed. If, however, we turn to the more fundamental physiological condition, namely that of the percentage saturation of the blood, the discrepancy largely disappears. Thus a glance at Figure VI shows that thirty-five minutes in an atmosphere containing four parts of carbon monoxide in ten thousand could induce twelve per cent blood saturation. Now blood which is twelve per cent saturated is in equilibrium to one part of carbon monoxide in ten thousand of air. In other words, a stay of several hours in an atmosphere of one part of carbon monoxide in ten thousand would involve the same percentage saturation as a stay of thirty-five minutes in four parts per ten thousand. Indeed, as the development of symptoms from carbon monoxide is wholly a question of oxygen deprivation it is safe to assert that a saturation of the blood up to sixteen per cent lasting for only a short period would involve less physiological effect than a prolonged period of saturation at twelve per cent.

On these grounds we have indicated in Figure VI two standards (1) for the blood at twelve per cent saturation or one to ten thousand tension for exposures of some hours, and (2) at sixteen per cent saturation, or 1.5 to ten thousand tension, for brief exposures.

The whole matter may be even more simply summed up in a single expression involving the time measured in hours, the concentration of carbon monoxide in the air in parts per ten thousand, and a constant for each degree of physiological effect. The physiological effects of all concentrations and times (within reasonable limits) may be then defined as follows:

(1) Times X Concentration — 3, no perceptible effect.
(2) Times X Concentration — 6, a just perceptible effect.
(3) Times X Concentration — 9, headache and nausea.
(4) Times X Concentration — 15, dangerous.

Physical exertion and increased breathing would reduce the constant in the first equation from three to two, one, or even less; and would affect the other equations correspondingly.

Any standard for any special conditions of time or concentration, within reasonable limits, based on these formulae, is sufficiently concordant both with the recommendations of Haldane and with the summary of our observations and conclusions contained in Figure VII.

Finally we may here quote from a letter recently received from Dr. Haldane. It was in answer to a letter from us stating the general trend of our observations and findings. In his letter Dr. Haldane says, " In the report on the Underground Railway the chemical standard which I recommended if steam traction was continued was .15 per cent of carbon dioxide, and I pointed out that this would contain about .01 per cent carbon monoxide. But the standard was not based primarily on the carbon monoxide, but on the general unpleasantness of the air. There was no definite evidence of people being upset by the carbon monoxide, though there was often .03 to .05 per cent at certain parts of the tunnel and stations; and I even found .066 per cent of carbon monoxide (with .89 per cent of carbon dioxide) on the platform of Gower Street Station (near University College). Passengers were never exposed long enough for ill effect, and the men at the stations were probably more or less acclimatized.

" At that time I did not know nearly so much about small percentages of carbon monoxide as I do now. Lorrain Smith and I made a lot of experiments on ourselves (Journ. of Physiol. XX, 1896 and XXII, 1897) to determine oxygen tension of arterial blood and came to the conclusions that anything less than .06 per cent produced no symptoms after several hours' exposure except

some shortness of breath on exertion. Our blood saturations only went to about twenty-eight per cent (in about one and one-half hours), and no further absorption occurred up to five hours. About a year later we tried a similar experiment, and found .06 per cent far too much for us. I tried again at Oxford later, and now found that even with about .03 the saturation gradually crept up during four or five hours to over thirty per cent. It became clear afterwards that in the first experiments we had both got acclimatized and were thus abnormally resistant to carbon monoxide.

"What I should now say is that with long exposures of several hours anything more than .02 per cent should be avoided. For exposures of less than an hour .05 per cent would not be really objectionable. As regards gases from motors, however, the smoke and smell might possibly be worse than the carbon monoxide. On this point I have no experience, though I have run across cases of poisoning where there does not seem to have been much smoke or smell.

"You will see from the above that my ideas about carbon monoxide coincide very closely with what your experiments point to. Lorrain Smith and I had not the least idea that by our daily experiments we had become acclimatized and ready to secrete oxygen as soon as our blood saturation rose to about twenty-five per cent. The absorption was simply stopped short as soon as oxygen secretion began; but an ordinary person does not secrete at this level, so the absorption goes creeping up for hours."

REFERENCES

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OBSERVATIONS IN LARGE GASSING CHAMBER

By H. W. Haggard

The experiments detailed in Section II involve exact, but rather artificial conditions. Exhaust gas is not pure carbon monoxide and the number of persons who could be tested in the six cubic meter chamber was quite limited. It appeared essential, therefore, to obtain confirmatory observations under as nearly real conditions, and on as many persons as possible.

For this purpose a brick building, thirty feet square, with walls twelve feet high at the side, and a hip roof, was erected. Its cubic capacity was approximately twelve thousand cubic feet of air. This is about the volume of a section of the vehicular tunnel which will contain one car when the traffic is active.

A Ford car was installed near the middle of this chamber. (Fig. VII.) A continuous stream of water ran into and out of its radiator to prevent overheating. The axles were supported on a wooden frame work so that the rear wheels turned clear of the ground. Against them were pressed two large wooden pulley wheels on a piece of heavy shafting. At the ends of the shafting were wooden paddle wheels. The engine of the car, therefore, ran with a fair load, and the power was expended in mixing the air in the chamber. The paddle wheels did this so effectively that in a number of tests practically uniform concentrations of exhaust gas were found simultaneously in all parts of the chamber.

The exhaust of the car was connected to a two inch iron pipe with a T and two valves. From one valve a pipe led to a large iron can (to equalize pressure) and to a gas meter, and discharged close to one of the paddle wheels, which reached in and distributed the gas. The pipe from the other valve led outside of the building. Thus, by adjusting the valves, all or any part of the exhaust gas could be discharged into the chamber and its volume read on the meter.

Samples of the exhaust gas unmixed with air were taken and analyzed for carbon monoxide in an Orsat apparatus, using ammoniacal cuprous chloride as the absorbent. The percentage ranged

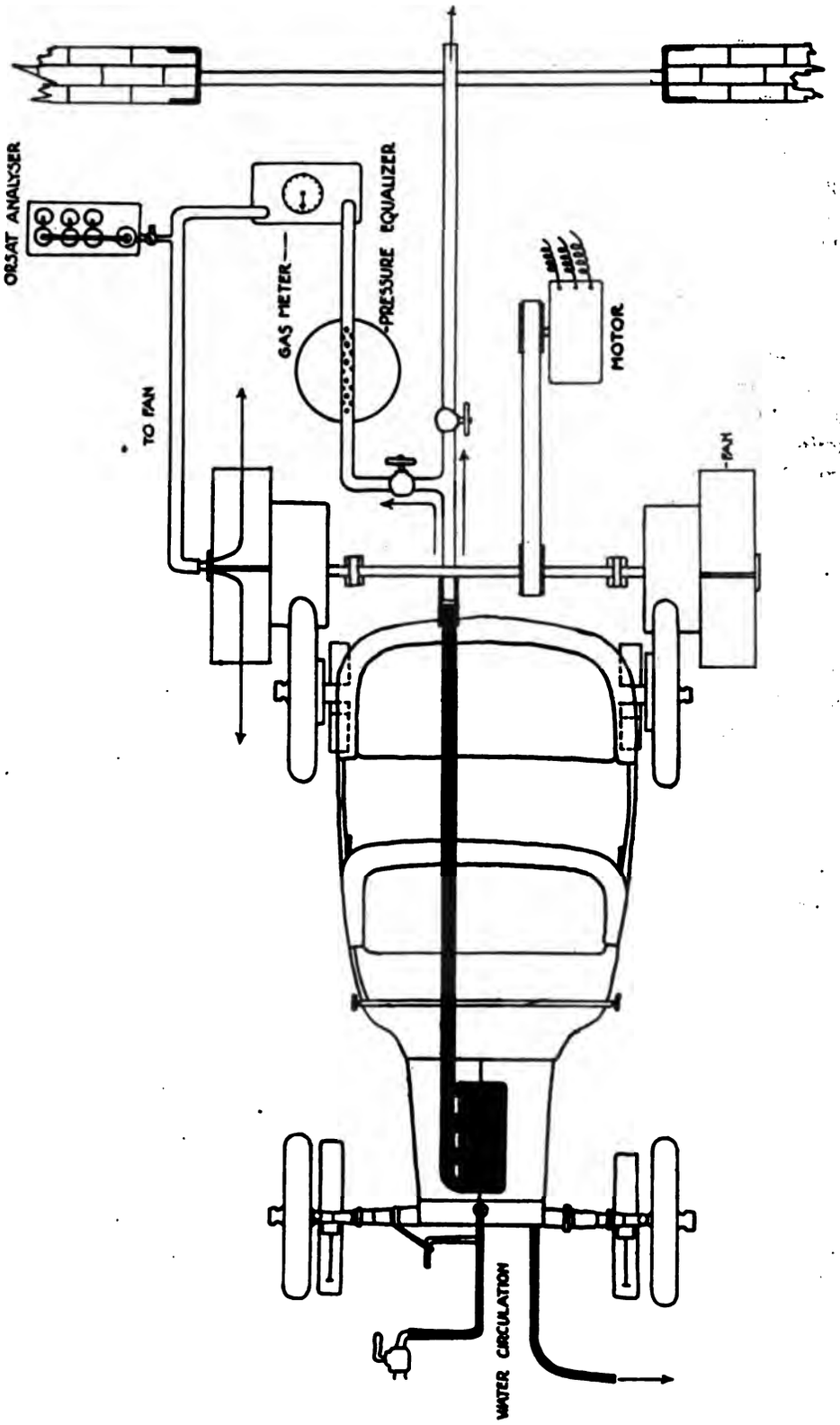
ORSAT ANALYSER
GAS METER
PRESSURE EQUALIZER
MOTOR
TO FAN
FAN
WATER CIRCULATION

Figure VII

between 5.5 and 6.8 per cent, with an average of about six per cent. The engine discharged a total of about twenty-five cubic feet of exhaust gas per minute from which we calculated that approximately 1.5 cubic feet of carbon monoxide were produced by the car per minute.

Diffusion from the chamber through the walls and roof, and through cracks around the doors and windows, was considerable. It amounted, when the engine was stopped, to a drop of about one-third of the concentration of carbon monoxide in fifteen minutes. Usually the entire exhaust of the engine was discharged through the meter into the chamber until the desired concentration of the carbon monoxide was approximately reached. Thereafter, a part of the gas was discharged out of doors, and only enough was passed into the chamber through the meter to compensate for loss by diffusion. Samples of the air in the chamber were taken at intervals during the period of exposure, and the amount of carbon monoxide determined either by means of iodine pentoxide (with a correction for vaporized gasoline), or by the blood-carmine method, or in both ways. Some discrepancies will be found in the analytical data, but it must be kept in mind that the methods are difficult and the amounts of the substance are miuute far beyond the range of ordinary gas analysis.

Considerable facility in controlling the concentration of carbon monoxide in the chamber was, with practice, attained. The experimental conditions were quite realistic. The car was old and had had rough treatment, and the engine was somewhat irregular in action. The exhaust gas was therefore contaminated with at least as much gasoline, oil, soot, and other substances, in addition to water vapor, carbon monoxide and carbon dioxide as may be met with in any well regulated vehicular tunnel. Owing to the fact that vaporized gasoline and other constituents of exhaust gas beside carbon monoxide act upon iodine pentoxide, as shown in Section XI, the figure .6 was determined as the factor by which it was necessary to multiply the iodine liberated in analysis of chamber air.

In this chamber groups of a dozen or more persons at a time sat or moved about for periods of one hour. In addition to the staff of this investigation a number of students of the Yale Medical School served as subjects. We take this opportunity to recognize the intelligent interest manifested, and the valuable service rendered by these young men and women.

After the tests the general condition and feelings of the subjects, particularly the occurrence or absence of headache, were noted. After they had breathed fresh air for five minutes, after leaving the chamber, samples of lung air were obtained by rebreathing repeatedly into a small rubber bag, and these samples were analyzed for carbon monoxide. In such analyses the gas found is that which was diffused out of the blood into the lung air, and the analytical data indicate therefore the tension of the carbon monoxide in the blood. The effect of running up and down four flights of stairs was noted also, as exercise markedly intensifies asphyxial symptoms.

The data obtained in these tests are given in the following pages. They are summarized by the statement that so long as the standard worked out in the previous section was not exceeded, no appreciable ill effects were induced in any of the numerous subjects. Above this standard, however, headache resulted in nearly all cases, and in some persons nausea and vomiting also occurred.

DETAILS OF OBSERVATIONS IN TUNNEL GASSING CHAMBER

Protocol 1. February 4, 1920. The engine of the car was started and maintained at a uniform speed for twenty minutes. Determinations were made of the carbon monoxide percentage in the exhaust from the engine (analyses with Orsat apparatus), and of the concentration of the gas in various parts of the chamber (by the iodine pentoxide method). For the latter purpose, two positions were chosen: No. 1, six feet to the west of the exhaust, and No. 2, nine feet to the north of the exhaust.

At the end of twenty minutes the smoke in the chamber had become quite disagreeable and the engine was stopped. The dispersing fans were continued in operation by the electric motor and air samples were taken at intervals. The pulmonary air of H. W. Haggard, who had been in the chamber up to this time, was taken a few moments after he left the chamber and analyzed. He had been actively at work on the car. The data obtained were as follows:

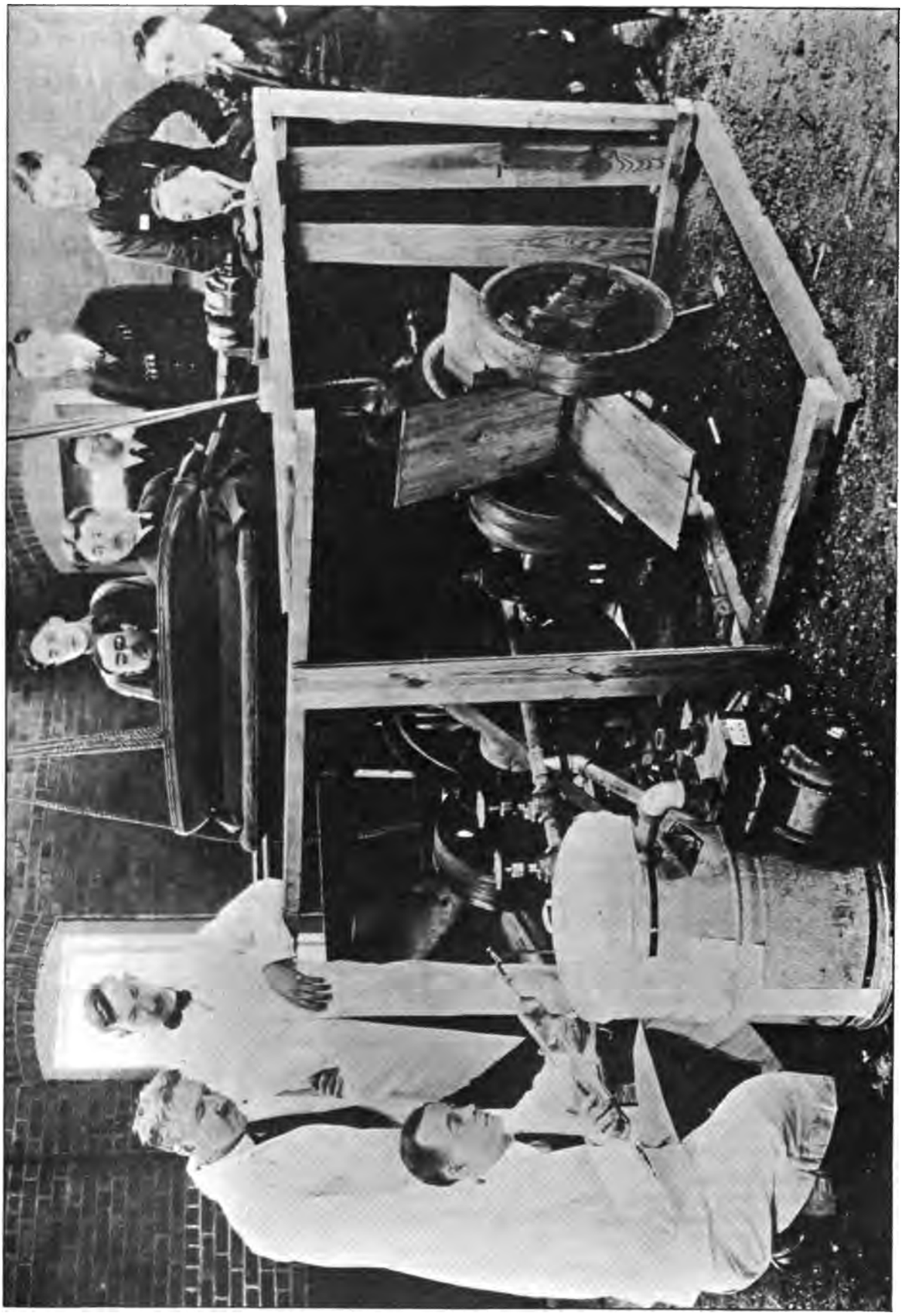

Figure VIII

EXPERIMENTAL CONDITIONS AND PHYSIOLOGICAL DATA

Time	Concentrations of CO in Positions 1	2	
Min.	Parts per 10,000		
0.....	0.5	0.5	Engine started.
5.....	3.0	3.0	Exhaust gas = 5.6 per cent. CO (by Orsat).
10.....	5.5	5.0	
15.....	6.5	7.0	Smoke very unpleasant.
20.....	8.0	8.0	Engine stopped. Smoke in chamber extremely irritating to eyes.
30.....	6.0	6.0	Pulmonary air of H. W. H., a few minutes after leaving the chamber, contained 3.1 parts CO. Severe headache and some nausea for four hours. Insomnia later.
90.....	1.5	...	Gas slowly diffusing out of chamber.

Protocol 2. February 5, 1920. The engine of the car was run until warm with the windows and door of the chamber open. It was then stopped and thirty minutes were allowed to elapse for the chamber to clear of gas. Door and windows were then closed; a control air sample was taken; and the engine was then started and run for five minutes at approximately the rate used in all of the following gassings in which no direct measure of the exhaust gas was made with the meter. After thus building up an initial concentration of gas, the engine was run intermittently as noted below.

Four subjects were in the chamber in different positions: position 1, S. Soby (age 28 years) northeast corner of chamber, fourteen feet from exhaust; position 2, Peter Integlia (boy 16 years) eight feet north of exhaust; position 3, W. H. Haggard (age 70 years) seven feet west of exhaust; position 4, H. W. Haggard (age 28 years) ambulatory.

Snap samples of air were taken by subjects in positions 1, 2 and 3 at the times indicated below. All four subjects also collected continuous samples of air uniformly throughout the entire period of gassing. All samples were analyzed by the iodine pentoxide method.

EXPERIMENTAL CONDITIONS AND PHYSIOLOGICAL DATA

Time	Engine	Concentration of CO in Positions 1	2	3	4	Remarks
Min.		Parts per 10,000				
0.....	Started.....	0.5	.....	.....	.....	
5.....	Stopped.....	2.5	2.5	2.5	.....	Exhaust gas — 6.2 per cent. CO (by Orsat)
13½.....	Started.....	.....	.....	.....	.....	
15.....	Stopped.....	2.5	2.5	2.5	.....	
23½.....	Started.....	3.0	2.0	2.5	.....	
25.....	Stopped.....	.....	.....	.....	.....	
33½.....	Started.....	.....	.....	.....	.....	
35.....	Stopped.....	.....	.....	.....	.....	
43½.....	Started.....	4.0	3.5	2.5	.....	Exhaust gas — 5.7 per cent. Co. (by Orsat)
45.....	Stopped.....	.....	.....	.....	.....	
53½.....	Started.....	4.0	3.5	5.0	.....	
55.....	Stopped.....	.....	.....	.....	.....	
Continuous samples.....		4.18	3.0	3.0	3.0	
Pulmonary air of four subjects immediately after leaving chamber..		1.51	1.58	1.39	1.64	No symptoms, either subjective or objective, occurred in any of the subjects.

Protocol 3. February 6, 1920. Procedure similar to previous protocol except that the engine was running during the entire period, the exhaust gas being turned into the chamber, or shunted to the outside, as desired, by an arrangement of piping and valves.

Five subjects were in the chamber in different positions: position 1, S. Soby, northeast corner of chamber, i.e., by the engine; position 2, Peter Integlia, middle west side of chamber; position 3, Mrs. R. M. Wunderlich, northwest corner; position 4, E. Hilton, ambulatory; position 5, H. W. Haggard, ambulatory.

EXPERIMENTAL CONDITIONS AND PHYSIOLOGICAL DATA

Time	Engine exhaust	Concentrations of CO in Positions 1	2	3	4	5	Remarks
Min.		Parts in 10,000					
0	Inside	.....	.....	.....	.....	.....	Exhaust gas — 6.4 per cent. CO (by Orsat)
6	Outside	3.0	3.0	.....	.....	.....	
14½	Inside	.....	.....	.....	.....	.....	
16	Outside	.....	.....	.....	.....	.....	
24½	Inside	3.5	3.0	.....	.....	.....	
26	Outside	.....	.....	.....	.....	.....	
34½	Inside	.....	.....	.....	.....	.....	
36	Outside	3.0	3.0	.....	.....	.....	
44½	Inside	.....	.....	.....	.....	.....	
46	Outside	.....	.....	.....	.....	.....	
54½	Inside	.....	.....	.....	.....	.....	
56	Outside	.....	.....	.....	.....	.....	
60		3.0	3.0	.....	.....	.....	
Continuous samples		3.0	3.0	.....	.....	.....	
Pulmonary air of five subjects immediately after leaving chamber		0.99	0.84	0.99	1.10	1.62	No symptoms, either subjective or objective, occurred in any of the subjects.

Protocol 4. February 11, 1920. Procedure similar to previous protocol. Continuous and snap samples of air were taken during the period of gassing in three places; position 1, northwest corner; position 2, northeast corner; position 3, middle of south side of chamber.

The number of persons in the chamber was eighteen, fifteen men and three women. Physiological data are given in the following table on p. 174. The first four subjects in the table were seated about position 1, the second four about position 2, and the next five about position 3. The last five were ambulatory. The normal pulse and respiration were observed on each subject some time before gassing, and the same data obtained again soon after gassing. The air analyses were made by the iodine pentoxide method. The engine was allowed to exhaust in the chamber for six minutes initially. The gas was then shunted to the outside for eight minutes. Thereafter the exhaust was discharged into the chamber for one and one-half minutes in each ten minutes. The conditions in the chamber as shown by analyses were as follows:

EXPERIMENTAL CONDITIONS

Time	Concentrations of CO in Positions 1	2	3
Min.	Parts in 10,000		
12	3.0	4.0	3.5
24	4.0	4.0	4.0
34	4.0	4.0	4.0
46	4.0	4.0	4.0
Continuous samples	3.5	4.98	3.5

PHYSIOLOGICAL DATA

SUBJECT	Sex	Duration exposure	CO in pulmonary air after gassing	PULSE						Symptoms
				NORMAL			AFTER GASSING			
				Rest	Exercise 1	Exercise 2	Rest	Exercise 1	Exercise 2	
			Parts in 10,000	Heart beats per minute						
H. Langer	Female.	1 hour	1.19	81	104	84	85	106	87	None.
C. Pepe	Male...	1 hour	1.12	90	126	114	74	119	102	None.
E. Tolstoi	Male...	1 hour	0.75	96	126	100	84	124	96	None.
E. Shorr	Male...	1 hour	0.99	75	150	85	80	148	90	None.
H. Bailey	Male...	1 hour	1.07	90	108	75	86	130	98	None.
E. Waters	Male...	1 hour	1.35	108	140	136	82	130	121	None.
T. Tamura	Male...	1 hour	1.44	81	108	94	76	106	92	None.
M. Hotchkiss	Female.	1 hour	1.16	.....	.....	.....	.....	.....	.....	None.
M. Bell	Female.	1 hour	1.21	.....	.....	.....	.....	.....	.....	None.
M. Glazer	Male...	1 hour	0.99	.....	.....	.....	.....	.....	.....	None.
E. Hilton	Male...	1 hour	1.06	.....	.....	.....	.....	.....	.....	None.
S. Soby	Male...	1 hour	1.24	.....	.....	.....	.....	.....	.....	None.
P. Integlia	Male...	1 hour	.....	.....	.....	.....	.....	.....	.....	None.
E. Levy	Male...	1 hour	0.99	.....	.....	.....	.....	.....	.....	None.
J. B. Snow	Male...	1 hour	1.27	.....	.....	.....	.....	.....	.....	None.
O. Singstad	Male...	1 hour	1.17	.....	.....	.....	.....	.....	.....	None.
Y. Henderson	Male...	46 min.	0.99	.....	.....	.....	.....	.....	.....	None.
H. W. Haggard	Male...	1 hour	1.33	.....	.....	.....	.....	.....	.....	None.

Protocol 5. February 14, 1920. The arrangements were in general similar to Protocols 3 and 4. All subjects were seated throughout gassing except the last (H.W.H) who was ambulatory.

Snap samples were taken in only one position, at the center of the north wall, while continuous samples were taken in position 1, center of north side; position 2, center of west side; and position 3, center of south side.

The durations of the exhaust gas flow into the chamber and the concentrations, as determined by the iodine pentoxide method, were as follows:

EXPERIMENTAL CONDITIONS

TIME	Engine Exhaust	CONCENTRATION OF CO IN POSITIONS			Remarks
		1	2	3	
Minutes		Parts in 10,000			
0	Inside	.....	.....	.....	Exhaust gas = 5.6 per cent CO (by Orsat).
8	Outside	13.38	8.0		
12	.....	11.54	6.5		
16	Inside	8.47	5.0		
18	Outside	6.95	4.0		
26	Inside	6.68	4.0		
28	Outside	9.78	6.0		
32	.....	16.42	10.0		
36	Inside	13.13	8.0		
38	Outside	17.28	10.0		
46	Inside	12.40	7.0	.....	Exhaust gas = 6.2 per cent CO (by Orsat).
48	Outside	15.51	9.0		
56	Inside	10.66	6.0		
58	Outside	13.95	8.5		
Continuous samples average		.....	7.0		

PHYSIOLOGICAL DATA

SUBJECT	Sex	Duration exposure	CO in pulmonary air after gassing	PULSE						Symptoms
				NORMAL			AFTER GASSING			
				Rest	Exercise		Rest	Exercise		
					1	2		1	2	
			Parts in 10,000	Heart beats per minute						
H. Bailey	Male	1 hour	1.04	78	120	96	86	120	116	None.
H. Farrell	Male	1 hour	0.86	76	120	92	72	124	96	None.
M. Glazer	Male	1 hour	2.03	72	120	96	75	104	72	Slight headache for five hours.
H. Harris	Male	1 hour	1.73	66	126	108	66	144	90	Slight headache for one hour.
J. Harris	Male	1 hour	1.13	78	112	96	72	142	98	Slightly dizzy on sudden move.
R. Kapsinow	Male	1 hour	2.00	84	140	88	88	110	88	Severe headache for four hours.
M. Riccitelli	Male	1 hour	0.51	72	144	90	78	140	78	None.
E. Shorr	Male	1 hour	0.92	78	144	116	88	148	188	None.
T. Tamura	Male	1 hour	1.11	72	148	95	98	146	98	None.
E. Tolstoi	Male	1 hour	0.95	72	120	78	90	132	104	None.
E. Wakeman	Male	1 hour	1.04	60	116	90	54	96	60	None.
L. Wakeman	Female	1 hour	1.76	72	109	83	64	115	68	Headache with some nausea.
E. Hilton	Male	1 hour	.....	....	....	....	....	....	....	
S. Soby	Male	1 hour	1.40	....	....	....	....	....	....	
H. Haggard	Male	1 hour	2.10	....	....	....	....	....	....	

Protocol 6. February 17, 1920. The arrangement of the engine exhaust previously described was altered by the introduction of a baffle can and a large bas meter into that portion of the piping which admitted the gas to the chamber. The volume of gas admitted into the chamber was thus more accurately controlled. A survey experiment identical with the gassing procedure carried out in protocol 5 was performed. Determinations were made upon the air in the chamber by the iodine pentoxide method, and samples were collected in dry flasks and analyzed for CO by the blood-carmine method.

The concentrations found by these methods, those estimated from meter readings, and analyses of exhaust gas by the Orsat apparatus, allowing for loss by diffusion, were as follows:

EXPERIMENTAL DATA

TIME	Engine exhaust	EXHAUST GAS		CONCENTRATION OF CO IN CHAMBER		
		By meter	By Orsat analysis	Estimated from meter and analysis	Iodine method	Blood-carmine method
Minutes		Cubic feet	Per cent	Parts in 10,000		
0	Inside	201	6.3	6	5.0	5.8
8	Outside					
16	Inside	53	.....	.....	.....	.....
18	Outside					
26	Inside	45	6.2	6	6.5	6.1
28	Outside					
36	Inside	61	.....	.....	.....	.....
38	Outside					
46	Inside	50	6.2	6	5.5	5.5
48	Outside					
56	Inside	50	.....	.....	.....	.....
58	Outside					

Protocol 7. February 18, 1920. General procedure as in Protocol 6. Air samples taken from chamber in dry flasks and carbon monoxide determined by the blood-carmine method. Pulmonary air determinations made by iodine pentoxide method. All subjects were seated during gassing except the last two.

EXPERIMENTAL CONDITIONS

TIME	Exhaust gas in chamber	CO in exhaust gas	Concentration of CO in chamber
Minutes	Cubic feet	Per cent	Parts in 10,000
0	150	5.9	....
6	....	....	....
15	40	....	4.2
25	40	....	....
35	40	6.1	3.8
45	44	....	....
55	40	6.3	4.4

PHYSIOLOGICAL DATA

SUBJECT	Sex	Duration exposure	CO in pulmonary air after gassing	PULSE						Symptoms
				NORMAL			AFTER GASSING			
				Rest	Exercise 1	Exercise 2	Rest	Exercise 1	Exercise 2	
			Parts in 10,000	Heart beats per minute						
T. Tamura	Male	1 hour	1.20	72	100	84	84	100	90	None.
H. Farrell	Male	1 hour	0.99	76	120	92	89	134	98	None.
E. Waters	Male	1 hour	0.55	82	136	96	94	104	98	None.
J. Harris	Male	1 hour	2.10	72	132	112	78	132	90	Faint headache.
B. Harris	Male	1 hour	1.60	66	126	108	66	144	84	None.
E. Tolstoi	Male	1 hour	1.10	72	120	86	90	144	100	None.
R. Kapsinow	Male	1 hour	3.20	100	132	112	100	108	100	None.
M. Riccitelli	Male	1 hour	0.99	72	141	89	91	143	86	None.
E. Shorr	Male	1 hour	1.21	78	144	116	84	148	100	None.
H. Langner	Female	1 hour	4.10	75	120	104	75	104	88	None.
E. Hall	Female	1 hour	1.75	80	116	96	84	105	88	None.
H. Bailey	Male	1 hour	0.79	78	120	96	80	132	102	None.
E. Wakeman	Male	1 hour	0.84	60	132	54	66	106	60	None.
J. Segel	Male	1 hour	2.61	64	120	64	144	90	....	None.
M. Glazer	Male	1 hour	0.62	72	130	96	84	124	96	None.
S. Soby	Male	1 hour	1.00	72	120	96	90	138	90	None.
H. Haggard	Male	1 hour	.....	....	....	....	....	....	....	None.

Protocol 8. March 6, 1920. General procedure as in previous protocol. Observations on eight men. Pulmonary air and chamber air samples determined by the blood-carmine method.

EXPERIMENTAL CONDITIONS

TIME	Engine exhaust through meter	Concentration of CO in chamber
Minutes	Cubic feet	Parts in 10,000
0	150	....
15	40	....
25	40	....
35	40	....
45	40	1.6
55	40	....
60	40	2.0

PHYSIOLOGICAL DATA

SUBJECT	Sex	Duration exposure	CO in pulmonary air after gassing	PULSE						Symptoms
				NORMAL			AFTER GASSING			
				Rest	Exercise		Rest	Exercise		
					1	2		1	2	
			Parts in 10,000	Heart beats per minute						
E. Shorr	Male	1 hour	0.76	78	144	116	84	150	112	None.
J. Fleming	Male	1 hour	0.97	84	130	96	90	142	92	None.
M. O'Connell	Male	1 hour	1.30	76	132	96	.....	136	98	None.
E. Waters	Male	1 hour	0.70	82	102	92	.....	130	96	None.
E. Tolstoi	Male	1 hour	0.57	72	120	72	72	132	78	None.
E. Wakeman	Male	1 hour	.....	53	132	54	54	144	60	None.
S. Soby	Male	1 hour	0.74	.....	.....	.....	.....	.....	.....	.....
H. Farrell	Male	1 hour	1.24	72	120	96	80	132	108	None.

Protocol 9, March 13, 1920. Procedure as in previous protocol. Observations on seventeen men and one woman. The subjects were for the most part quite active during this experiment. Analyses of pulmonary and chamber air samples were made by Haldane blood method.

EXPERIMENTAL CONDITIONS

TIME	Exhaust gas through meter	Exhaust gas by Orsat analysis	Concentration of CO in chamber
Minutes	Cubic feet	Per cent	Parts in 10,000
0	300	6.4	....
10	80	....	....
15	....	....	6.8
20	75	....	....
30	82	....	9.0
35	....	6.6	....
40	78	....	8.6
50	78	....	....
60	....	....	9.3

From these figures the mean concentration of carbon monoxide breathed for one hour may be estimated to have been at least nine parts per ten thousand of air, and from the Orsat figures perhaps two or three parts higher.

PHYSIOLOGICAL DATA

SUBJECT	Sex	Duration exposure	CO in pulmonary air after gassing	PULSE						Symptons
				NORMAL			AFTER GASSING			
				Rest	Exercise 1	Exercise 2	Rest	Exercise 1	Exercise 2	
			Parts in 10,000	Heart beats per minute						
G Gildersleve....	Male.....	1 hour	2.7	82	116	108	96	152	120	Dizziness, extreme headache and some nausea.
A. Vanderberg....	Male.....	1 hour	2.9	72	156	84	90	180	120	Throbbing headache for several hours followed by general lethergy for twenty-four hours.
A. Dreher.....	Male.....	1 hour	2.2	82	100	90	105	165	110	Headache, nausea, chill.
J. Olean.....	Male.....	1 hour	1.9	82	144	110	102	170	126	Dizziness immediately after gassing, sharp headache for nine hours.
L. Peroff.....	Male....	1 hour	1.8	74	130	110	100	152	122	Throbbing headache for nine hours.
M. O'Connell.....	Male.....	1 hour	3.0	72	120	96	108	150	132	Frontal headache for six hours.
J. Fleming.....	Male.....	1 hour	2.7	86	93	90	130	140	120	Severe headache, vomited, in bed five hours.
E. Waters.....	Male.....	1 hour	2.7	82	138	102	120	150	142	Severe headache for twenty hours, legs weak.
M. Glazer.....	Male.....	1 hour	2.7	60	108	88	84	144	90	Severe headache lasting five hours.
H. Farrell.....	Male.....	1 hour	2.5	76	132	96	90	140	104	Severe headache (occipital) for eight hours.
E. Tolstoi.....	Male.....	1 hour	1.9	72	120	72	120	156	90	Severe headache, dizzy, nauseated, ringing in ears, symptoms lasted for seven hours.
E. Shorr.....	Male.....	1 hour	2.5	74	120	86	116	166	156	Persistent headache and nausea for eight hours.
H. Bailey.....	Male.....	1 hour	1.6	78	108	96	80	120	100	Severe headache and nausea for six hours.
E. Wakeman.....	Male.....	1 hour	1.8	50	130	54	60	160	90	Severe headache, faintness for a few hours.
H. Langer.....	Female...	1 hour	2.2	72	120	104	108	168	108	Pounding in ears, violent headache and nausea, headache for forty-eight hours.
A. Wakeman.....	Male.....	1 hour	2.0	54	120	72	68	120	68	Headache and nausea.
D. Susman.....	Male.....	1 hour	2.2	80	100	88	120	150	130	Severe headache and vomiting.
J. Sigel.....	Male.....	1 hour	1.8	72	84	80	....	152	144	Very faint and weak, severe headache for seventy-two hours.

EXPOSURE OF HORSES TO EXHAUST GAS

A few observations were made on two horses. They were of the Percheron and weighed between 1400 and 1800 pounds, one bay and the other white. They were U. S. Army Artillery horses. We are greatly indebted to Colonel R. E. D. Hoyle, Commanding Officer, Field Artillery Unit, R. O. T. C., stationed at Yale University, for the loan of the animals.

The car and motor were taken outside of the tunnel gassing chamber and the exhaust gas piped to the inside. The horses were not hitched, but were allowed to move about freely inside the chamber. In each experiment a blood sample was drawn from the ear before and after gassing. The results of the three experiments were as follows:

DATE	Time	Concentration of CO in chamber	PERCENTAGE SATURATION OF THE BLOOD		Remarks
			White horse	Bay horse	
		Parts in 10,000			
March 17, 1920.....	1 hour...	2.5	.....	11	No symptoms.
March 17, 1920.....	1 hour...	5.0	20	20	No symptoms.
March 19, 1920.....	1 hour...	5.0	23	25	No symptoms.

Owing to the fact that the dispersing fans were not in operation we believe that the concentration of gas was quite variable in different parts of the chamber; and it is probable that the atmosphere which the horses actually breathed contained considerably higher concentrations of CO than the figures given in the table.

VI

OBSERVATIONS IN GARAGES AND IN THE GRAND CENTRAL STATION, NEW YORK CITY

The occurrence of fatalities in small private garages during cold weather has become so frequent an item of news that the public is becoming aware of the danger. Evidently if a car, while warming up, gives off one cubic foot of carbon monoxide per minute in a room 10 x 10 x 20 feet, the atmosphere will, apart from diffusion, reach the dangerous concentration fifteen parts in ten thousand in three minutes. Owing to the insidious and usually accidental character of carbon monoxide poisoning in such garages, however, nothing bearing particularly on our problem is to be learned from them which could not be more accurately determined in our experimental chamber.

At first it would appear that important information might be obtained from the conditions occurring in large public garages and repair shops. On investigation of a number of such places we found that even in those recently built and supplied (usually more or less imperfectly) with artificial ventilation the employees frequently have slight headaches, while severe headache, nausea and emotional disturbances, ranging from mere unreasonableness up to hysterical mirth, anger or grief, or even maniacal manifestations, are not very unusual. There seems to be general recognition that " it is not gasoline but the burnt gas " which produces these conditions. Our inquiries have also elicited information regarding an occasional case of death in which the victim had crawled under a car when its own engine was running, or the engine of a standing car ahead was " idling."

When, however, it came to getting samples of air for analysis from garages we soon found that we could get anything that we wanted, high or low, and that the figures had, therefore, little value without more elaborate supervision of the personnel than we could provide.

Conditions such as may occur in tunnels appear to be afforded in the taxicab driveway and stand below the Grand Central Railway Station, New York City. The general public passes through this place, many thousands per day. The taxicab drivers sometimes wait half an hour for a passenger and the starters and markers are on duty for four or five hours at a time.

We learned on inquiry that up to a few months before this investigation a type of car had been in use which produced a considerable amount of smoke and that at that time headache and nausea were common. Recently, however, another type of car producing very little smoke has been introduced and symptoms of gassing appear now to be rare.

In order to define the conditions members of the staff of this investigation spent several hours near the starters' position and took a number of samples of air for analysis, with the following results:

March 12, 1920. A mild damp afternoon and evening. 5.45 p. m. Soon after a number of cars had gone through. Carbon monoxide in air was 0.36 parts in ten thousand.

9.45 p.m. After forty cars had gone through in fifteen minutes. Carbon monoxide in air was 1.36 parts in ten thousand.

10.35 p.m. After three cars had passed in ten minutes. Carbon monoxide was 0.45 parts in ten thousand.

11.30 p.m. Fifteen cars through in five minutes, sample taken ten minutes later contained 1.78 parts in ten thousand.

On another occasion a series of samples were taken and yielded the following figures: 0.45, 1.78, 0.36, 1.36, 2.12 and 1.47.

It appears from these data that the air is occasionally vitiated for a time as much as two parts of carbon monoxide in ten thousand, but that with the ventilation provided by large fans the concentration of carbon monoxide soon falls again decidedly below one part in ten thousand.

There are now, so far as we can learn, no complaints from the public, and the taxicab drivers have only an occasional headache, when a line of cars stand for a time with their engines running.

VII

THE COMPARATIVE TOXICITY OF PURE CARBON MONOXIDE, ILLUMINATING GAS, EXHAUST GAS FROM GASOLINE, EXHAUST GAS FROM COAL DISTILLATE AND GASOLINE VAPOR

By H. W. Haggard

The general agreement between the experiments with pure carbon monoxide mixed with air in Section II and the results with exhaust gas in Section V indicates strongly that in the concentrations occurring in the large chamber carbon monoxide was the only substance of sufficient toxicity and present in sufficient amount to have any appreciable considerable physiological effect. All of the data in both of these series of experiments were, however, based upon low concentrations of the gas. The deductions from them might not apply equally to high and lethal concentrations.

We have thought it well to check these results therefore by means of observations on animals in high concentrations of gas. For this purpose dogs were used. The animal in each case was placed in a chamber of about three feet cube of plate glass. The gas to be tested was mixed with air in a gasometer of several hundred liters capacity, so that the carbon monoxide concentration was about 0.3 to 0.4 per cent or 30 to 40 parts in ten thousand. From the gasometer the gas mixture was passed into the chamber through a tube by a small electrically driven air blower. Another tube from the chamber led outdoors.

Usually the gas was run in at such a rate that the animal was at the point of death in thirty to thirty-five minutes. The animal was then removed from the chamber and a sample of blood was drawn for analysis by the carmine titration method.

(a) *Experiments with pure carbon monoxide with air:* In this atmosphere the animals became unconscious with no more apparent discomfort than if anaesthetized with ether. The blood of five dogs at the point of death contained the following percentages of carbon monoxide:

87, 82, 84, 79, 88 Average 84

(b) *Experiments with illuminating gas mixed with air:* In such an atmosphere the symptoms during intoxication differed in some respects from the preceding group. There was in all cases more rapid collapse, and distinctly greater respiratory excitement. Nausea and vomiting, which were lacking in the experiments with pure carbon monoxide, occurred in all of this second group. These observations and the fact that a lower percentage of saturation of the blood with carbon monoxide causes death indicate that illuminating gas contains some substance, or substances, which render it distinctly more toxic than an equal amount of pure carbon monoxide. The blood of the five dogs used in these experiments contained at the point of death the following percentages of carbon monoxide:

74, 67, 63, 76, 71. Average 70

(c) *Experiments with exhaust gas from a car using gasoline:* For these tests the three commonest varieties of gasoline sold locally were used successively. A large rubber bag was attached to the exhaust of a car (one in good condition with an efficient and smooth running engine), while it was standing with the engine running "idle." This gas was analyzed for carbon monoxide by means of an Orsat apparatus in the usual way. The gas was then mixed with air in the large gasometer to approximately the same concentration of carbon monoxide as in the previous experiments. It was then administered to animals in the glass chamber. In these experiments the animals were at the point of death in approximately the same time as in the first series of experiments under (a) above. The symptoms were similar to those from pure carbon monoxide and unlike those with illuminating gas. The percentages of carbon monoxide in the blood were also similar to the first but higher than the second series. Evidently carbon monoxide was here practically the only

toxic substance. The blood of the five dogs used in this group of experiments contained at the point of death the following percentages of carbon monoxide:

84, 86, 83, 81, 81. Average 83.

(d) *Experiments with exhaust gas from a car using coal distillate:* We are indebted to the New Haven Gas Company for the opportunity to make these tests. The Company very kindly sent a car charged with coal distillate to the laboratory and allowed us to obtain a bag of exhaust gas as in the preceding experiments. Two dogs were exposed to this gas, exactly as the animals had been exposed in the previous experiments to exhaust from gasoline, and died with symptoms like, but more marked than, those of the dogs poisoned with illuminating gas.

The blood of these two animals had a decidedly brownish tinge indicating a marked destructive influence upon the hemoglobin of the blood. It is known that benzene has such an effect.

The composition of the coal distillate according to figures kindly furnished by the chemist of the Gas Company was:

Benzol	69.0 percent
Tuluol	15.5 percent
Solvent Naphtha	13.5 percent
Heavy Naphtha	2.0 percent
Total	100.0

The blood of the two dogs used in these experiments contained at the point of death the following percentages of carbon monoxide:

60, 64. Average 62.

(e) *Experiments with gasoline vapor:* There is a tendency — which we have encountered repeatedly among persons unacquainted with the potency of carbon monoxide as an asphyxiant — to think that gasoline vapor, that is, volatilized unburned gasoline, is the chief, or at least a considerable factor in the toxicity of exhaust gas.

Such, however, is not the case. It is true that, as the experiments to be here reported will show, gasoline vapor has an intoxicating effect; but the toxicity is vastly less than that of the same concentration of carbon monoxide.

Furthermore, the combustion of one liter of gasoline vapor in the engine produces roughly two liters of carbon monoxide. In fact, it is probable that if a man or animal were shut up in a small garage with a four cylinder car in three cylinders of which the explosions were " missing," the carbon monoxide produced by the one active cylinder would induce death before the three other cylinders had discharged enough gasoline vapor to induce, by itself, slight nausea.

Our experiments were carried out on dogs in the small glass chamber (Fig. IX). A stream of air of twenty liters per minute was blown through a flask partly filled with gasoline and on through a short piece of tubing into the chamber. The flask stood on an electrically heated plate and the dosage of gasoline was controlled by the amount of heat.

A few preliminary experiments were run in which the concentration of gasoline vapor was not accurately determined. In general, the physiological effects were identical with those in the following experiments, in which an effort was made to obtain a maximum degree of precision (Fig. X).

EXPERIMENT 1. DOG, MALE, 12 KILOS. "STANDARD" GASOLINE

Time	Concentration of Vapor	Notes
Minutes	Parts in 10,000	
0	0	Vaporization started.
12	32	No symptoms.
20	79	Slightly depressed, licks nose.
28	89	Slight general tremor, restless.
31	....	Falls, violent epileptiform convulsions.
36	100	Tries to stand, but falls repeatedly, general muscular tremor, salivating.
42	156	Animal becoming weak, unable to stand, fairly quiet although conscious, chamber cloudy with condensing gasoline vapor.
65	176	Conscious, quiet, temperature of chamber 20° C.
73	175	Animal taken out of chamber and laid on the floor.
0	....	Can just lift head.
2	....	Unable to stand although making violent efforts.
5	....	Rolls on the floor, chronic muscular spasms.
9	....	Raises body on fore legs, limbs rigid.
12	....	Stands very unsteadily with legs wide apart.
13	....	Falls attempting to walk.
16	....	Attention attracted by calling, walks but falls repeatedly.
22	....	Walks fairly well, slight general muscle tremor.
Next day	....	Slightly depressed, no appetite, drinks water.
Second day	....	Apparently perfectly normal.

EXPERIMENT 2. DOG, MALE, 11 KILOS. "SOCONY" GASOLINE

Time	Concentration of Vapor	Notes
Minutes	Parts in 10,000	
0	0	Vaporization started.
19	76	Animal slightly restless.
30	102	Violent spasms. Unable to stand. Head retracted, general rigidity.
38	162	Almost continuous epileptiform convulsions.
46	184	More quiet, breathing shallow, conscious.
61	196	Conscious, quiet, chamber temperature 22° C.
64	....	Animal taken out of chamber and laid on the floor.
0	....	Barely conscious.
4	....	Violent epileptiform convulsions for 62 seconds, during which respiration stopped.
8	....	Continued convulsions.
12	....	Convulsions less violent.
20	....	Attempts to stand.
25	....	Able to stand but falls on attempting to walk.
30	....	Walks but staggers.
Next day	....	Depressed, no appetite.
Second day	....	Appears normal except or slight inflammation of one eye.

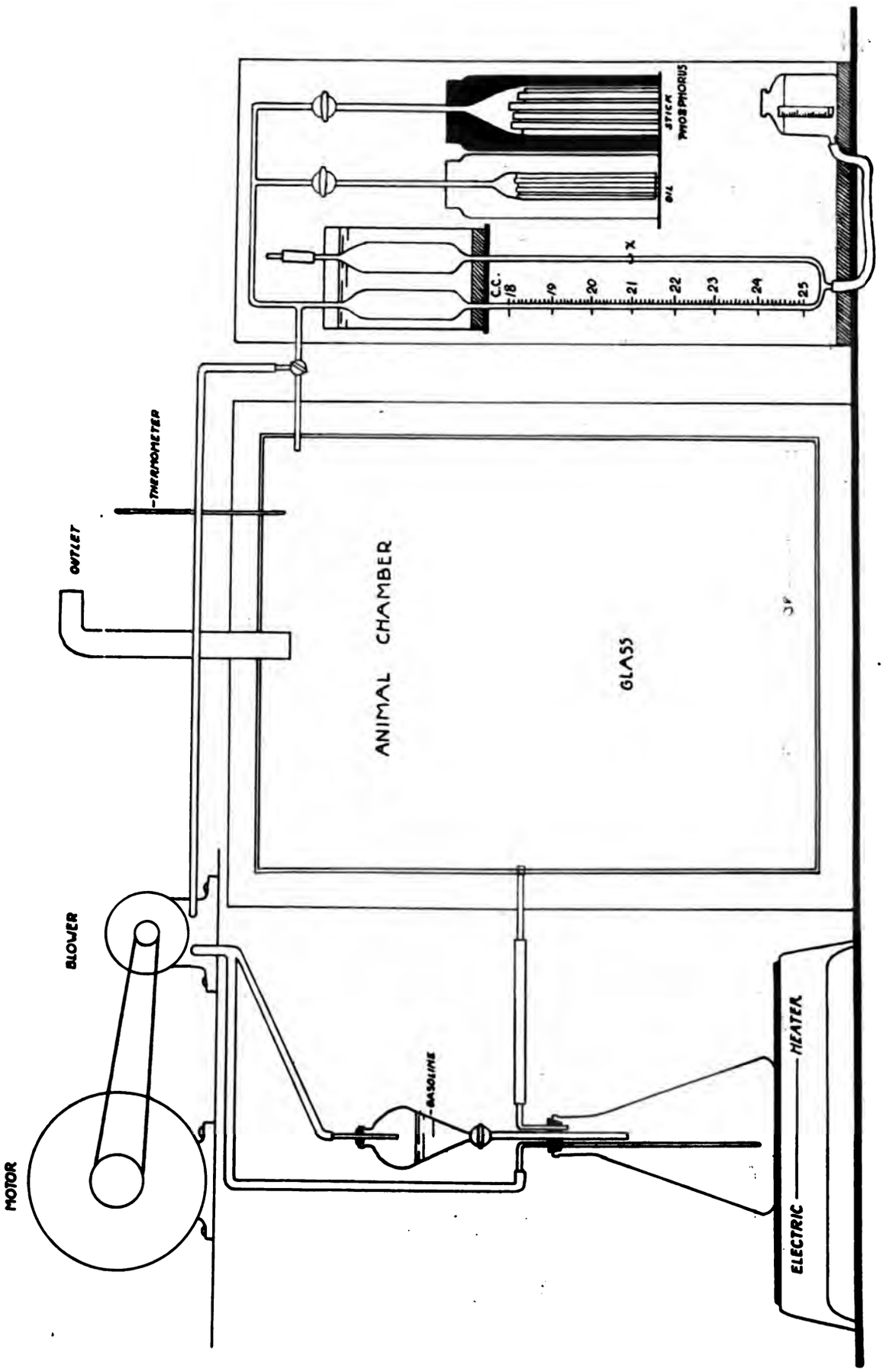
STICK PHOSPHORUS
OIL
TAR
X
C.C.
18
19
20
21
22
23
24
25
THERMOMETER
OUTLET
ANIMAL CHAMBER
GLASS
BLOWER
GASOLINE
HEATER
ELECTRIC
MOTOR

Figure IX

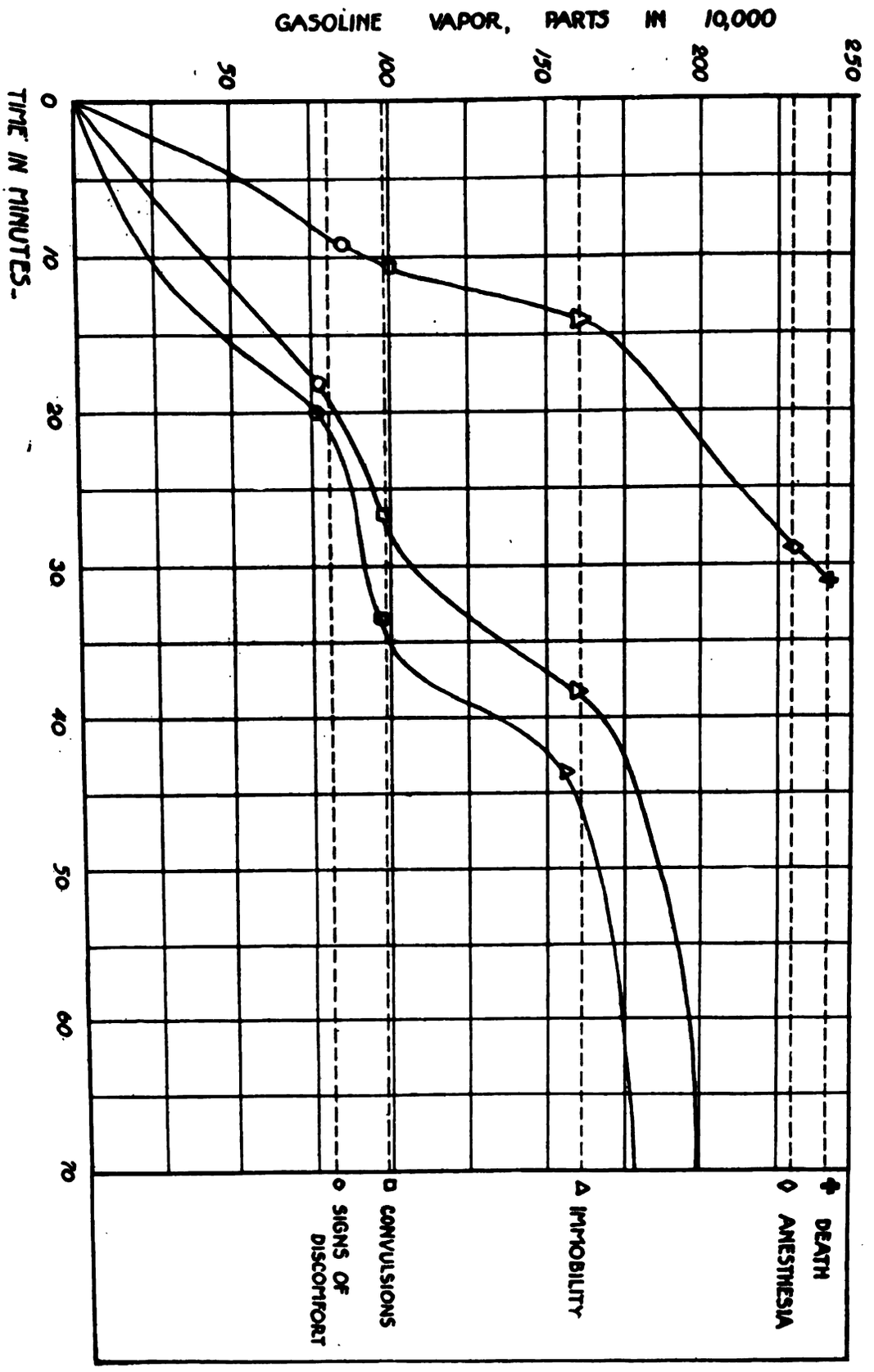
GASOLINE VAPOR, PARTS IN 10,000
50
100
150
200
250
TIME IN MINUTES.
0
10
20
30
40
50
60
70
SIGNS OF DISCOMFORT
CONVULSIONS
IMMOBILITY
ANESTHESIA
DEATH

Figure X

EXPERIMENT 3. DOG, MALE, 16 KILOS. "GOOD GULF" GASOLINE

Time	Concentration of Vapor	Notes
Minutes	Parts in 10,000	
0	0	Vaporization started.
5	52	No symptoms.
10	96	Restless, licking nose.
13	160	Slight general convulsion, unable to stand.
19	....	Violent epileptiform convu'sions.
22	200	Muscular rigidity, very shallow breathing.
31	243	Unconscious, shallow breathing, temperature in chamber 26°C.
37	238	Feeble spasms.
39	....	Dog dead.

The data of these experiments are plotted in Figure X. The close agreement between the concentrations at which the various symptom phases occurred is noteworthy. In general gasoline vapor has an anaesthetic action somewhat like that of ethyl ether but with marked irritation of the cerebral cortex. Thus the stage of excitement, common in other anaesthesia, is marked by convulsions under gasoline vapor. The stage of full anaesthesia, between consciousness and death, is very narrow.

VIII

THE TENSION OF CARBON MONOXIDE IN THE PULMONARY AIR AFTER GASSING

In the lungs the blood is so freely exposed to the air that it very quickly takes up or gives off gas until equilibrium in this respect between the contents of the air sacs and the blood vessels is established. Thus for instance it is a well recognized method of physiology to determine the tension of the carbon dioxide in the arterial blood of a normal man by analyzing a sample of air obtained by a deep expiration.

If a similar method is applicable to determining the tension of carbon monoxide in the blood after gassing the experimental utility of the procedure is considerable. For, by means of the tension applied to the carbon monoxide hemoglobin dissociation curve the percentage saturation of the blood may be determined.

When this method first suggested itself to us we made some experiments to check its validity and obtained quite satisfactory results. Later, however, in using this method and particularly in the data obtained from some of the experiments in the large gassing chamber, results were obtained which we had every reason to believe were much too low. The time at our disposal was, however, insufficient for a thorough critical investigation of the reliability and limits of accuracy of the method.

According to Haldane's views the lungs are capable at times of actively secreting oxygen inward and thus forcing carbon monoxide outward. Under such conditions the tension of carbon monoxide in the pulmonary air would be found to be greater than the corresponding percentage saturation of the blood in the body. Evidently this process does not explain the discrepancies above referred to, for in our experience the figures from the pulmonary air instead of being too high were too low to correspond with the degree of blood saturation.

The possibility also presents itself that in the process of obtaining pulmonary air by rebreathing into a bag the tension of oxygen falls. The tendency of the carbon monoxide in the blood to come off into the air (and its tension in the pulmonary air) would fall correspondingly. If this occurs, the figures from analyses by the iodine pentoxide method should show a corresponding divergence. Actually, however, in our check determinations fairly concordant results were obtained when samples

of pulmonary air were analyzed both by the iodine pentoxide and by the blood-carmine methods. On the other hand, determinations of the percentage saturation of the blood (equilibrated in the body) and of the carbon monoxide in samples of pulmonary air taken simultaneously sometimes checked almost perfectly and sometimes diverged widely,— the figures for the air being much too low.

The apparatus employed is shown in Figure XI.

All the methods need further critical study.

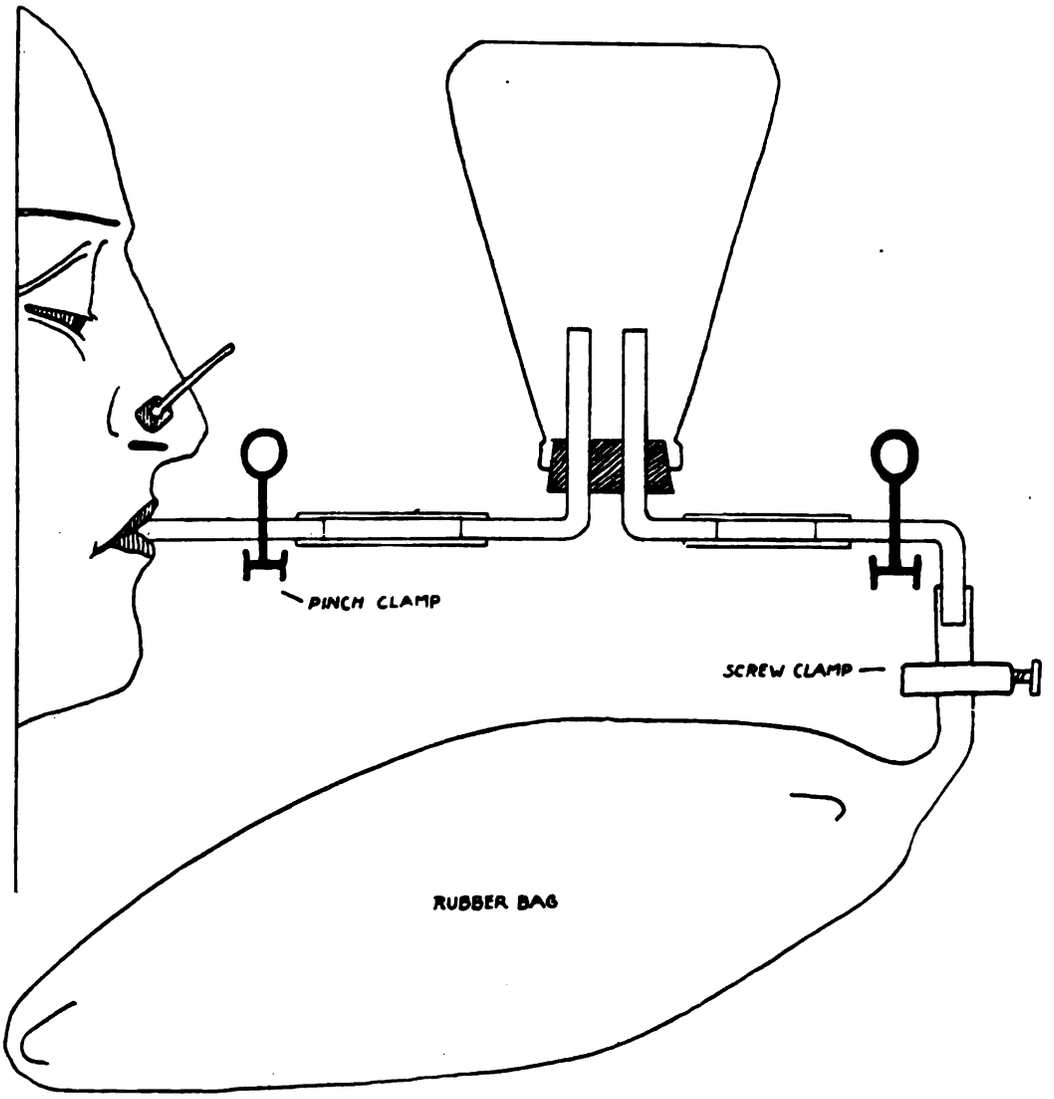

Figure XI

Protocol 1. The pulmonary air immediately after gassing was obtained from several individuals by means of the apparatus shown in Figure XI with variations in the amount of rebreathing as follows:

(a) The subject after a normal inspiration expired into a rubber bag. This air was then rebreathed five times.

(b) Air was rebreathed similarly eight times.

(c) Five rebreathings, then after a rest of one minute the same air was rebreathed eight times.

(d) The same air was subjected to three periods of rebreathing, of five times, eight times, and ten times, with one minute periods of rest between. Determinations of carbon monoxide were made by the iodine pentoxide method with the following results:

SUBJECT	CARBON MONOXIDE IN PULMONARY AIR AFTER GASSING			
	a	b	c	d
	Parts in 10,000			
H. W. Haggard	1.98	1.94	1.64	1.80
C. Rowlands	1.30	1.50	1.22	.....
M. C. Teague	1.26	1.00	1.31	1.33
I. D. Ross	1.20	1.38	1.00	1.40
F. Wentsel, Jr	1.40	1.20	1.42	1.10

On these data, procedure (a) appears adequate and was therefore adopted.

The degree of agreement which may be obtained at times between the figures for the tension of carbon monoxide in the pulmonary air after gassing and those for the percentage saturation of the blood are shown in the following data in which in the fourth column the figures are those for percentage saturations corresponding to the tensions in the second column.

SUBJECT	CO in Pulmonary Air	CO Found in Blood	Blood CO as Calculated from Pulmonary Air
	Parts in 10,000	Per cent Saturation	Per cent Saturation
F. Wentsel	1.33	18	17
W. B. Fulton	1.30	17	17
M. C. Teague	1.30	21	17
C. Rowlands	1.26	16	16
H. W. Haggard	1.98	25	22

On the other hand, results so discrepant as the following were obtained in an experiment near the close of our work.

The subject, C. C. Stockman, spent one hour in the six cubic meter chamber in eight parts of carbon monoxide. A series of samples of blood were thereafter drawn from a finger and the pulmonary air was analyzed both by the iodine pentoxide and the blood carmine methods. Results were as follows:

Pulmonary Air by Iodine Method	Pulmonary Air by Blood-carmine Method	Carbon Monoxide in Blood from Finger	Corresponding Tension of CO
Parts in 10,000	Parts in 10,000	Per cent Saturation	Parts in 10,000
1.38	1.40	27.8	2.6
0.91	1.20	27.5	2.6
1.09	1.20	16.2	1.3
1.02	0.90	19.6	1.7
0.48	0.70	5.1	0.4
0.67	0.60	0.0	0.0
0.57	0.40	0.0	0.0
0.40	....	....	

Evidently the figures in Columns 2 and 3, instead of corresponding with those of columns 4 and 5, are only about half as large; an error in the pulmonary air method of about minus fifty per cent.

IX

THE COMBINATION OF CARBON MONOXIDE AND HEMOGLOBIN AND ITS ANALYTICAL APPLICATIONS

By A. L. Prince

The method which we have used for the determination of the percentage saturation of blood with carbon monoxide is that of titration with carmine as devised by Haldane. It is based upon the change of color induced in hemoglobin by its union with carbon monoxide.

When normal blood is sufficiently diluted with water it assumes a yellowish red color the intensity of which depends on the amount of oxy-hemoglobin present in the solution. On the other hand, when blood is exposed to an atmosphere containing carbon monoxide, this gas combines with the hemoglobin, according to definite laws. The resulting carbon monoxide-hemoglobin, when diluted, has a characteristic pink color which contrasts strongly with that of dilute normal blood. The intensity of the pink tint is proportional to the amount of carbon monoxide which the blood has absorbed.

In order to use this color for purposes of analysis a standard blood solution is prepared containing a definite percentage of hemoglobin. A portion of this solution is completely saturated with carbon monoxide; the other is kept for comparison. Thus two color values are obtained, first the intense pink color of the one hundred per cent saturated sample, and second the yellowish red color of the normal.

As Haldane has shown, the pink color of the fully saturated sample may be imitated by a mixture of dilute blood and carmine. Thus by adding standard carmine solution to the standard normal blood solution all degrees of pinkness may be obtained ranging from zero to that of one hundred per cent saturation with carbon monoxide.

In order to analyze blood for carbon monoxide, it is necessary to determine the proportionate amounts of carmine solution required, when added to a measured quantity of standard normal blood solution to match colorimetrically, first, the blood solution of unknown saturation, and second a sample of the same blood fully saturated with carbon monoxide. A few drops of blood from the finger of a person who has been exposed to carbon monoxide may be thus analyzed.

This method may also be applied to the determination of small quantities of carbon monoxide in atmospheric air. A standard blood solution is brought into gaseous equilibrium with the air to be analyzed, and the percentage saturation of the blood determined by means of carmine as above. The value for the air is then obtained from the dissociation curve.

This curve is obtained by equilibrating blood solutions with accurately prepared mixtures of carbon monoxide in air, and then analyzing the blood for its percentage saturation with the gas. Once this curve has been determined the concentration of carbon monoxide in the (unknown) air mixture may be obtained by equilibrating some blood solution with the air, i.e., freely exposing it to this air, then analyzing it, and applying the blood value to the dissociation curve. In this curve the ordinates indicate the percentage saturation of the blood, and the abscissae express the concentration of carbon monoxide in the air mixture under examination.

The characteristics of the carbon monoxide-hemoglobin dissociation curve have been studied in considerable detail by Haldane and his co-workers. As their work is contained in a number of papers with variations and developments through many years, we have thought it worth while to bring together here the principal results. In general, our observations confirm their results, which we have amplified by observations on the blood of as large a number of persons as possible, in the time available, both in health and disease.

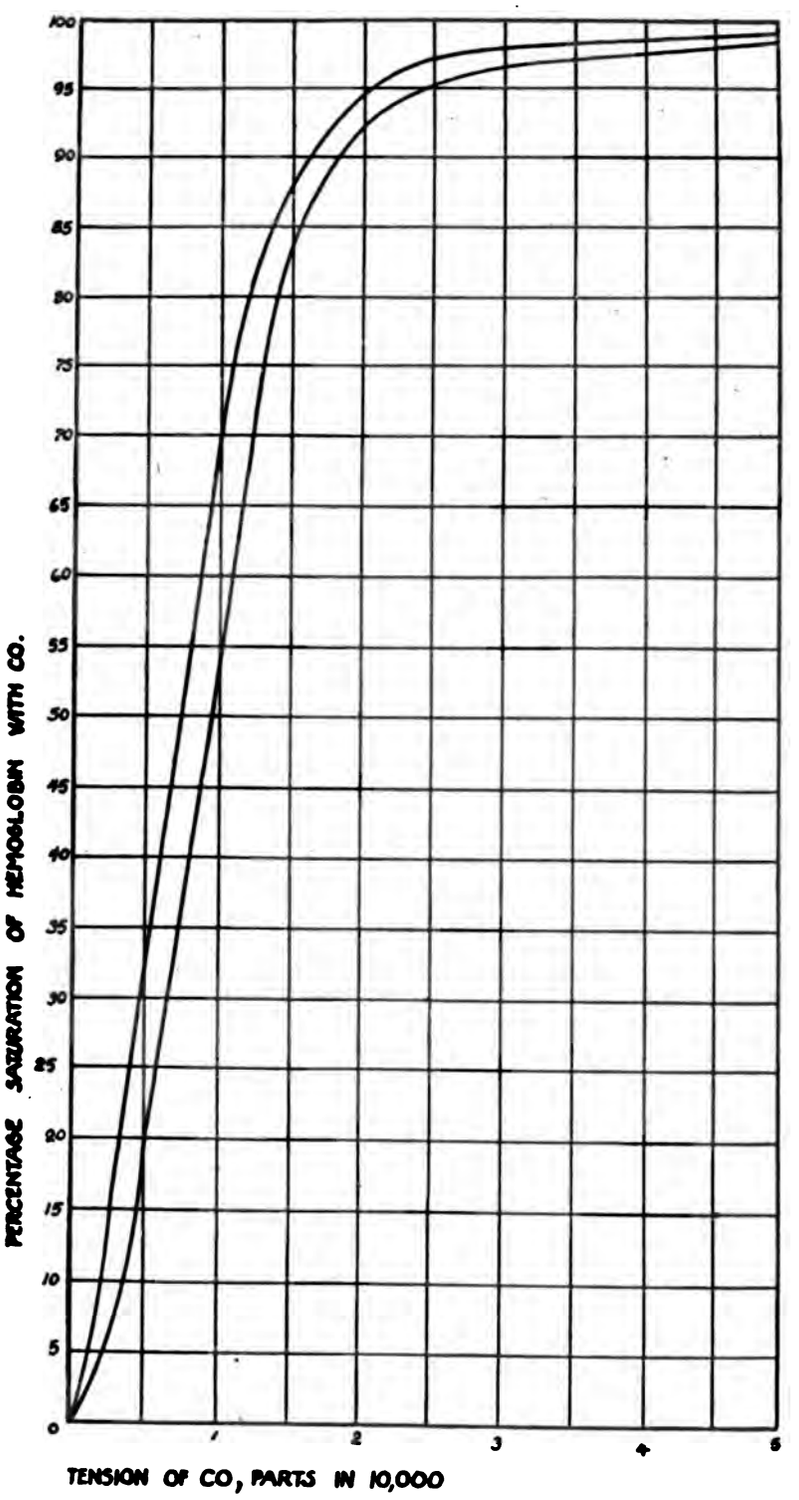
PERCENTAGE SATURATION OF HEMOGLOBIN WITH CO.
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
1
2
3
4
5
TENSION OF CO, PARTS IN 10,000

Figure XII

X

CHARACTERISTICS OF THE CARBON MONOXIDE DISSOCIATION CURVE AND THE EXTENT OF INDIVIDUAL VARIATIONS

By A. L. Prince

When whole or diluted blood is equilibrated (i.e. exposed until gaseous equilibrium is reached) with a mixture of carbon monoxide and a physiologically inert gas, such as nitrogen or hydrogen, the percentage of saturation of the hemoglobin with carbon monoxide is determined by the tension (partial pressure) of this gas in the mixture. If the tension of carbon monoxide is varied the ratio of carbon monoxide hemoglobin to reduced hemoglobin is correspondingly affected. These variations are expressed by a curve (Figure XII). It will be noted that even with low tensions of carbon monoxide (two to three parts in ten thousand parts of nitrogen) the hemoglobin is nearly completely saturated with this gas, indicating that the attraction of hemoglobin for carbon monoxide is very strong.

In the presence of oxygen, however, the percentage of saturation of hemoglobin with carbon monoxide is considerably modified; for hemoglobin likewise attracts oxygen, although less intensely. The ratio of carbon monoxide-hemoglobin to oxy-hemoglobin depends now on the balance between two forces, each of which is the resultant, or product, of two other forces. The first two are the tension of oxygen (TO_2) in the gas mixture, and the affinity of oxygen for hemoglobin (AO_2). The second two are the tension of carbon monoxide (TC_o), and its affinity (A_{co}). The relative amounts of oxy-hemoglobin (Hb_{o_2}) and carbon monoxide-hemoglobin (Hb_{co}) (and with oxygen tensions about ten per cent of an atmosphere practically all of the hemoglobin is combined with one gas or the other) may then be expressed thus:

$$\frac{T_{co} \times A_{co}}{T_{o_2} \times A_{o_2}} = \frac{Hb_{co} \text{ and}}{Hbo_2.}$$

$$\frac{T_{co} \times A_{co}}{(T_{o_2} \times A_{o_2}) + (T_{co} \times A_{co})} = \frac{Hb_{co}}{Hb_{co} + Hbo_2} = \text{Per cent saturation with CO.}$$

The character of the carbon monoxide dissociation curve in the presence of air (21.0 per cent oxygen) is shown in Figure XIII.

It is known that the affinity of hemoglobin for carbon monoxide varies slightly in different individuals, and even more in the blood of various species. But the possibility of variations in human bloods under conditions of health and disease have not received special consideration.

On this point we have collected a considerable amount of data (Table IV). The results are shown in the dissociation curves given in Figure XIV. The determinations were made at a temperature of 20° C., and the curves are therefore slightly steeper than are those of Haldane and Douglas at 38° C.

It will be noted that while the percentage of hemoglobin in the individuals whom we have examined varied from 38 per cent (a case of pernicious anemia) to 110 per cent the variations in the carbon monoxide dissociation curves are but slight and bear no relation to the percentage of hemoglobin.

The carbon monoxide-dissociation curve is also affected by the temperature at which the blood is equilibrated with a given carbon monoxide mixture. As shown in Figure XV the affinity of hemoglobin for carbon monoxide varies inversely with the temperature.

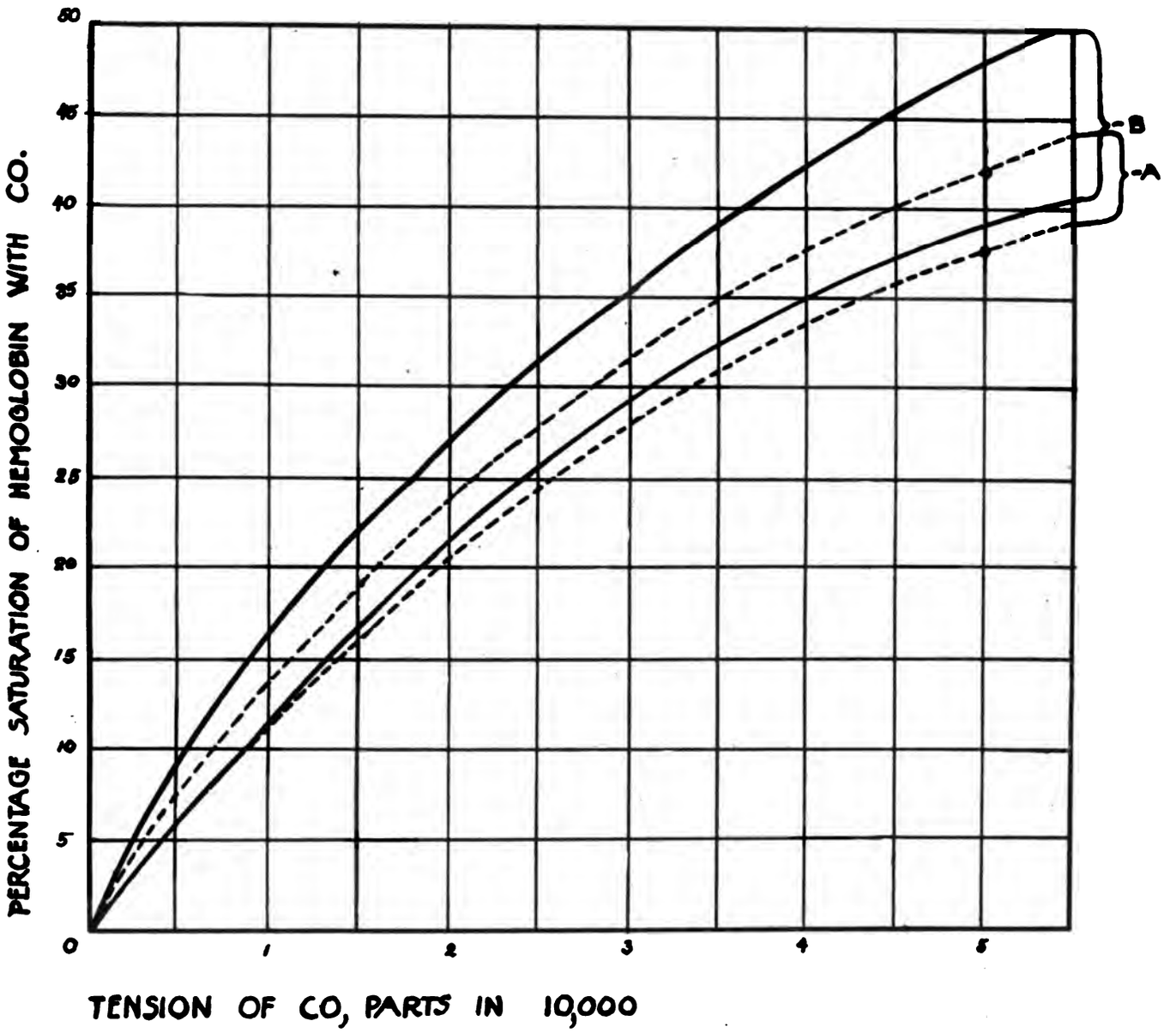
PERCENTAGE SATURATION OF HEMOGLOBIN WITH CO.
50
45
40
35
30
25
20
15
10
5
0
1
2
3
4
5
B
A
TENSION OF CO, PARTS IN 10,000

Figure XIII

TABLE IV

Subject	Age	Sex	Condition	Hemoglobin	Curve Number Figure	Affinity at 20° C.
	Years			Percentage		Oxygen: carbon monoxide
H. S.	59	Male	Pernicious anemia	38	4	1:310
M. G.	27	Female	Pernicious anemia with recent transfusion	60	3	1:323
W. F.	38	Male	Diabetes mellitus	60	4	1:310
J. B.	28	Male	Pulmonary tuberculosis	80	8	1:286
M. H.	3	Female	Broncho pneumonia	80	5	1:298
H. C.	31	Male	Chronic endocarditis	85	3	1:323
E. K.	12	Male	Lobar pneumonia	85	8	1:254
M. M.	14	Female	Diphtheria (convalescent)	85	7	1:275
M. B.	48	Female	Tumor of spinal cord	85	2	1:364
F. B.	53	Female	Mucous colitis	85	3	1:323
S. C.	8	Female	Tuberculosis of hip joint	90	7	1:275
S. C.	30	Male	Diabetes mellitus	100	3	1:323
F. W.	20	Male	Normal	100	6	1:286
M. C. T.	30	Male	Normal	100	1	1:378
R. M. W.	23	Female	Normal	100	1	1:378
A. L. P.	36	Male	Normal	105	2	1:364
Y. H.	46	Male	Normal	110	7	1:275
H. W. H.	28	Male	Normal	110	3	1:323

As the affinities of carbon monoxide and oxygen for hemoglobin are approximately as 300 is to 1, changes of oxygen tension in the carbon monoxide mixture with which the blood is equilibrated have a distinct effect upon the percentage saturation of the hemoglobin with carbon monoxide. With uniform tensions of carbon monoxide a decrease in the oxygen tension in the gas mixture increases the percentage saturation of hemoglobin with carbon monoxide as shown in Figure XVII. Evidently, the influence of low oxygen tension on the combining power of carbon monoxide with hemoglobin must be taken into account in making determinations of carbon monoxide in air in which the oxygen may have been reduced by respiration, by combustion, or other causes.

In a carbon monoxide and carbon dioxide mixture free from oxygen, changes in the tension of carbon dioxide also modify the carbon monoxide-dissociation curve. As shown in Figure XVII, the curve shifts to the right as the carbon dioxide tension rises. The influence of carbon dioxide on the affinity of carbon monoxide is dependent in great part if not wholly on the change in reaction of the blood (rise in hydrogen in concentration) occasioned by the presence of this gas.

When blood, on the other hand, is equilibrated with carbon monoxide, oxygen, and carbon dioxide at the usual tensions found in the pulmonary air the carbon monoxide dissociation curve is not appreciably affected by the presence of carbon dioxide in the gas mixture. This indicates that small changes in the reaction of the blood affect the affinities of carbon monoxide and oxygen for hemoglobin to the same extent.

From the behavior of the carbon monoxide dissociation curve under the conditions described above, it is evident that in utilizing this curve for the determination of small quantities of carbon monoxide in atmospheric and alveolar air, uniform temperatures should be maintained and corrections made for variations in the oxygen tension of the carbon monoxide mixture with which the blood is equilibrated.

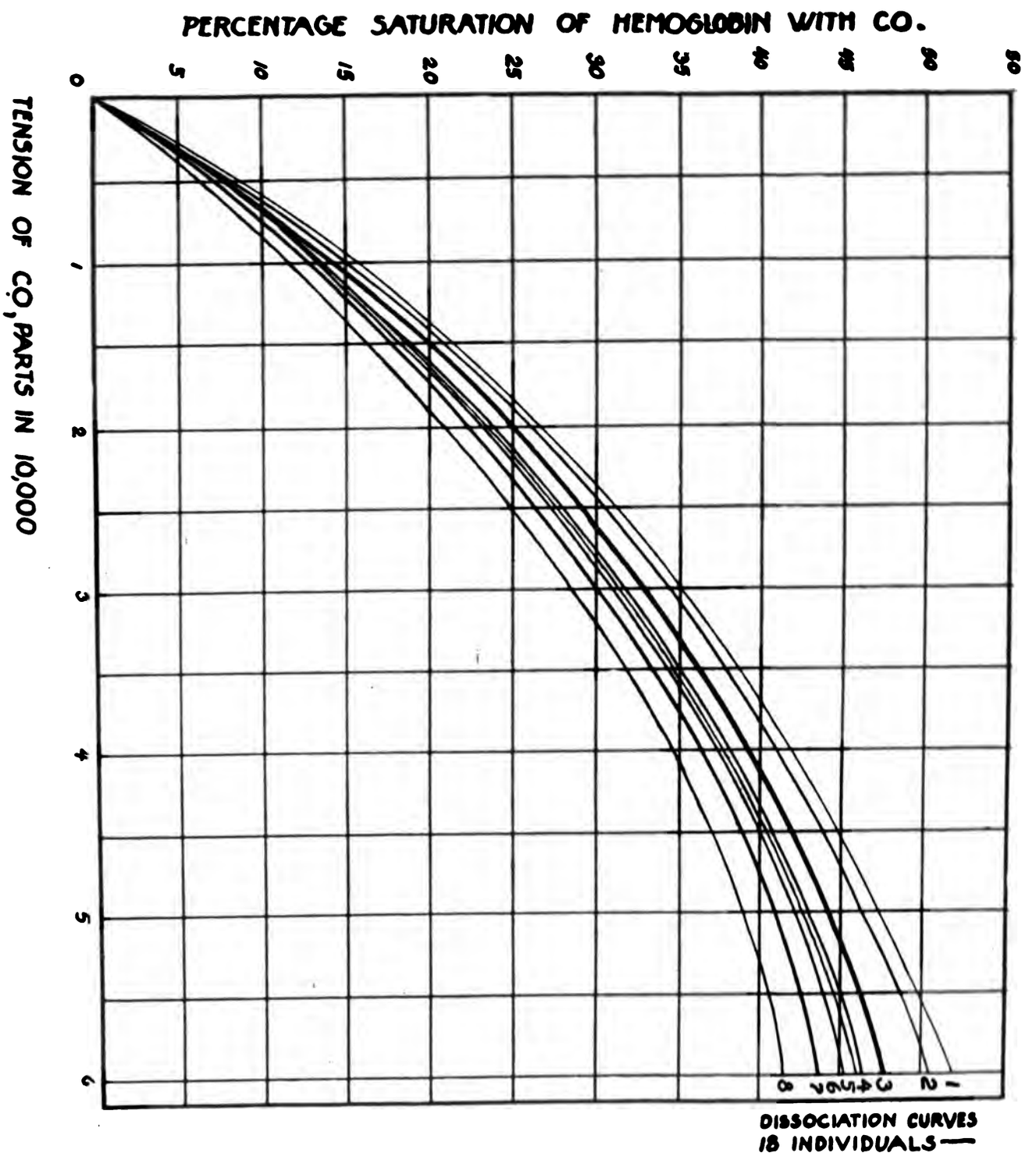
PERCENTAGE SATURATION OF HEMOGLOBIN WITH CO.
0
5
10
15
20
25
30
35
40
45
50
TENSION OF CO, PARTS IN 10,000
1
2
3
4
5
6
DISSOCIATION CURVES
18 INDIVIDUALS

Figure XIV

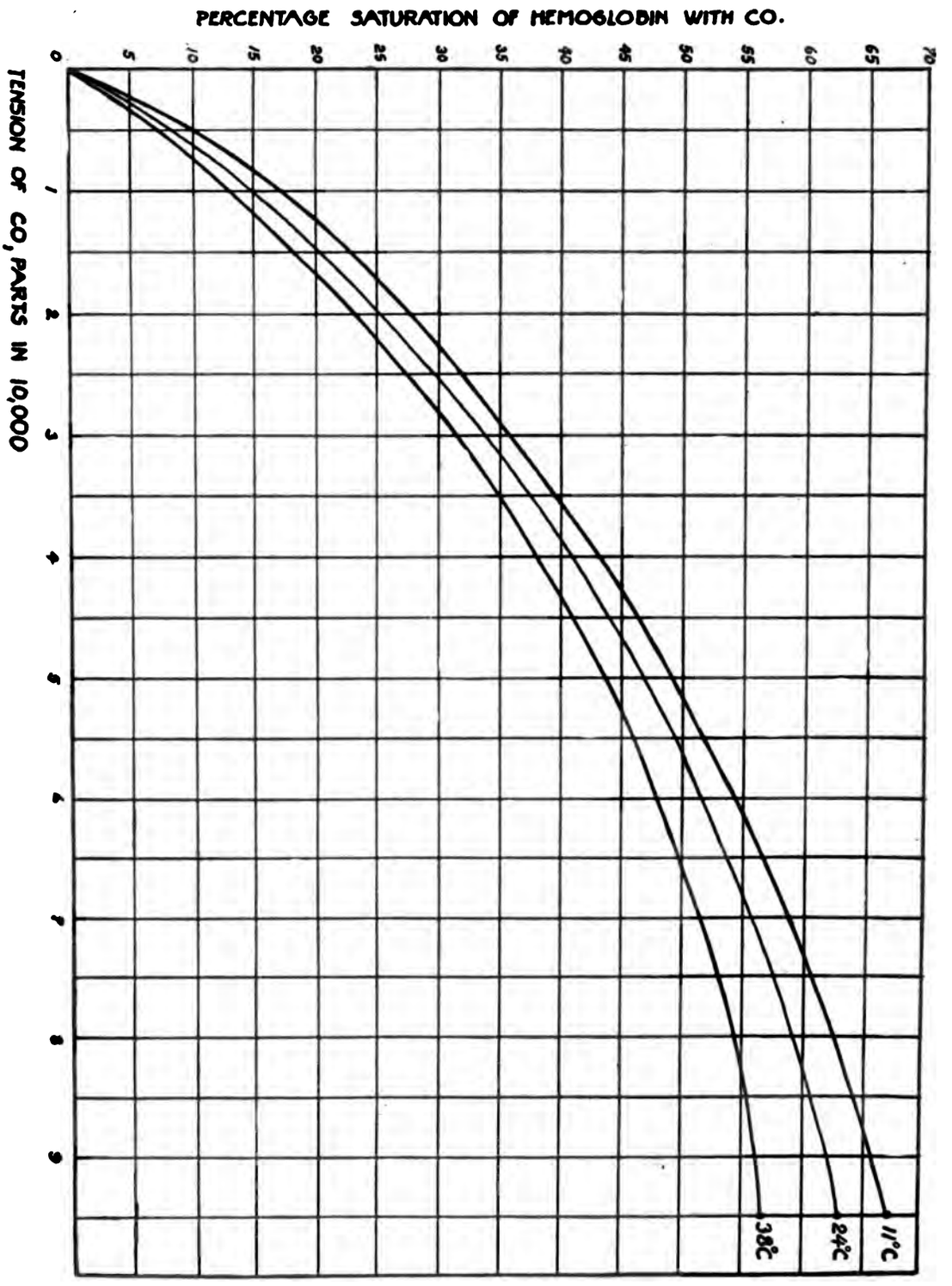
PERCENTAGE SATURATION OF HEMOGLOBIN WITH CO.
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
TENSION OF CO, PARTS IN 10,000
1
2
3
4
5
6
7
8
9
38°C
24°C
11°C

Figure XV

The Determination of the Concentration of Carbon Monoxide in Atmospheric Air by the Blood-Carmine Method

1. Method of preparation of standard blood.

The diluted blood used for equilibration is prepared as follows: With a Gower pipette 20 cubic millimeters of blood are drawn from the finger and diluted in a test tube containing exactly 4 c.c. of ammoniated distilled water (one part of strong ammonia to 200 parts of distilled water). The test tubes used should be of uniform internal diameter (about 10 m.m.) and of about six c.c. capacity. Using this pipetted standard for comparison sufficient blood is drawn from the same individual and diluted in ammoniated water until the diluted blood and the pipetted standard have by color exactly the same hemoglobin content. If a large number of samples are to be examined, several hundred cubic centimeters of the diluted blood can be prepared as follows:

The finger is stabbed with a large needle or lanced and the blood is shed into a 250 c.c. Erlenmeyer flask containing 200 c.c. of ammoniated distilled water until the color of the diluted blood approximates the color of the pipetted standard (10 cubic millimeters of blood in 4 c.c. of ammoniated distilled water). The pipetted standard is then saturated with illuminating gas and compared with a 4 c.c. sample of the flask dilution also saturated with the same gas. The blood dilutions when thus saturated with carbon monoxide assume a deep pink color which greatly facilitate the matching of the two samples. As the flask sample will be deeper in tint, ammoniated water is gradually measured into it from a narrow burette and the samples matched with the pipetted sample until the tints are equal. The amount of ammoniated water required to produce equality of tint being known, an aliquot portion of ammoniated water is added to the flask solution.

In matching the samples, the character of the light is important. Very bright light and reflected light from neighboring buildings should be avoided. The best conditions are obtained on a cloudy day and by north light.

Several precautions have to be observed in the preparation of the standard blood. The glassware should be absolutely clean. Soluble glass should be avoided as it leads to rapid " bleaching " of the blood solution. The best results are obtained with Pyrex and Jena Erlenmeyer flasks.

Direct sunlight, or even diffused daylight " bleach " the blood solution rapidly; therefore, all manipulations except the color matching should be carried out in a darkened room. The standard once prepared is kept in the dark, and in a cool place.

2. Collection of air sample for analysis.

If the air of the chamber, room, garage, or other place where the presence of carbon monoxide is suspected, is to be analyzed by means of the blood carmine method, a 250 c.c. Erlenmeyer flask is filled with the air. A rubber hand bulb may be used for this purpose or the air may be drawn in by repeated inspirations from a rubber tube inserted in the flask. The tube should be withdrawn from the flask before the end of each inspiration to prevent possible expiration into the flask. The flask is then closed with a rubber stopper.

3. Equilibration of standard blood solution with air containing CO.

Four cubic millimeters of the standard blood dilution are drawn into a clean Luer syringe, and the needle inserted through the rubber stopper of the Erlenmeyer flask containing the air sample. Another needle is inserted through the stopper as a vent to equalize the pressure. The fluid is then injected into the flask, and then both needles are withdrawn.

Equilibration of the air and blood solution may be obtained by shaking the flask in a dark room for one-half hour, but when several samples are to be examined an equilibrator such as that shown in Figure XVIII is convenient. It consists of an inclined platform rotated by an electric motor. The rate of rotation and the inclination are adjusted so that a film of diluted blood flows over the bottom of the flask at each turn. With mixtures up to six parts of carbon monoxide in ten thousand rotation for half an hour with twenty revolutions of the equilibrator per minute is sufficient for complete equilibration. For high concentrations three-quarters of an hour are required

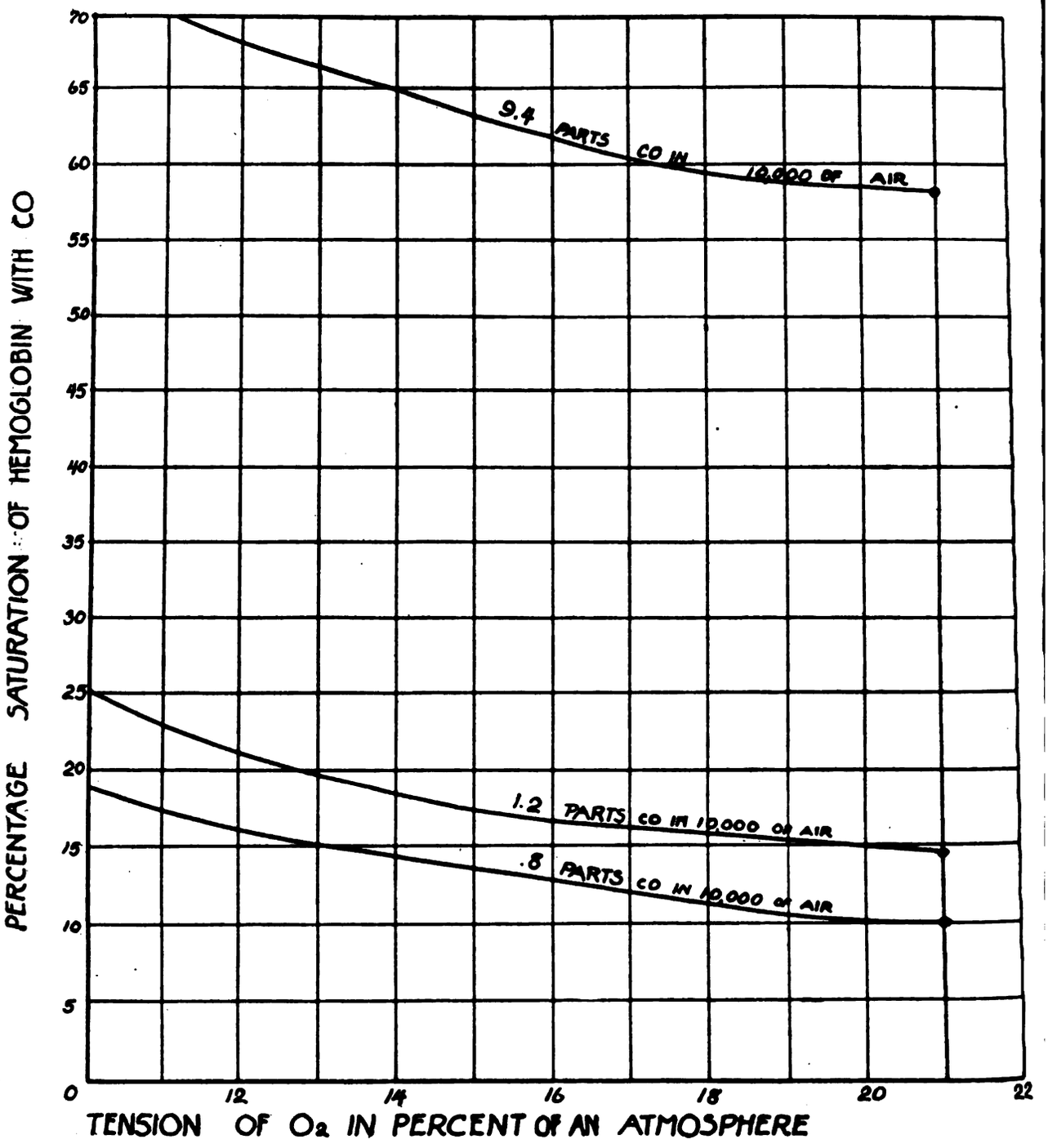
PERCENTAGE SATURATION OF HEMOGLOBIN WITH CO
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
9.4 PARTS CO IN 10,000 OF AIR
1.2 PARTS CO IN 10,000 OF AIR
.8 PARTS CO IN 10,000 OF AIR
12
14
16
18
20
22
TENSION OF O2 IN PERCENT OF AN ATMOSPHERE

Figure XVI

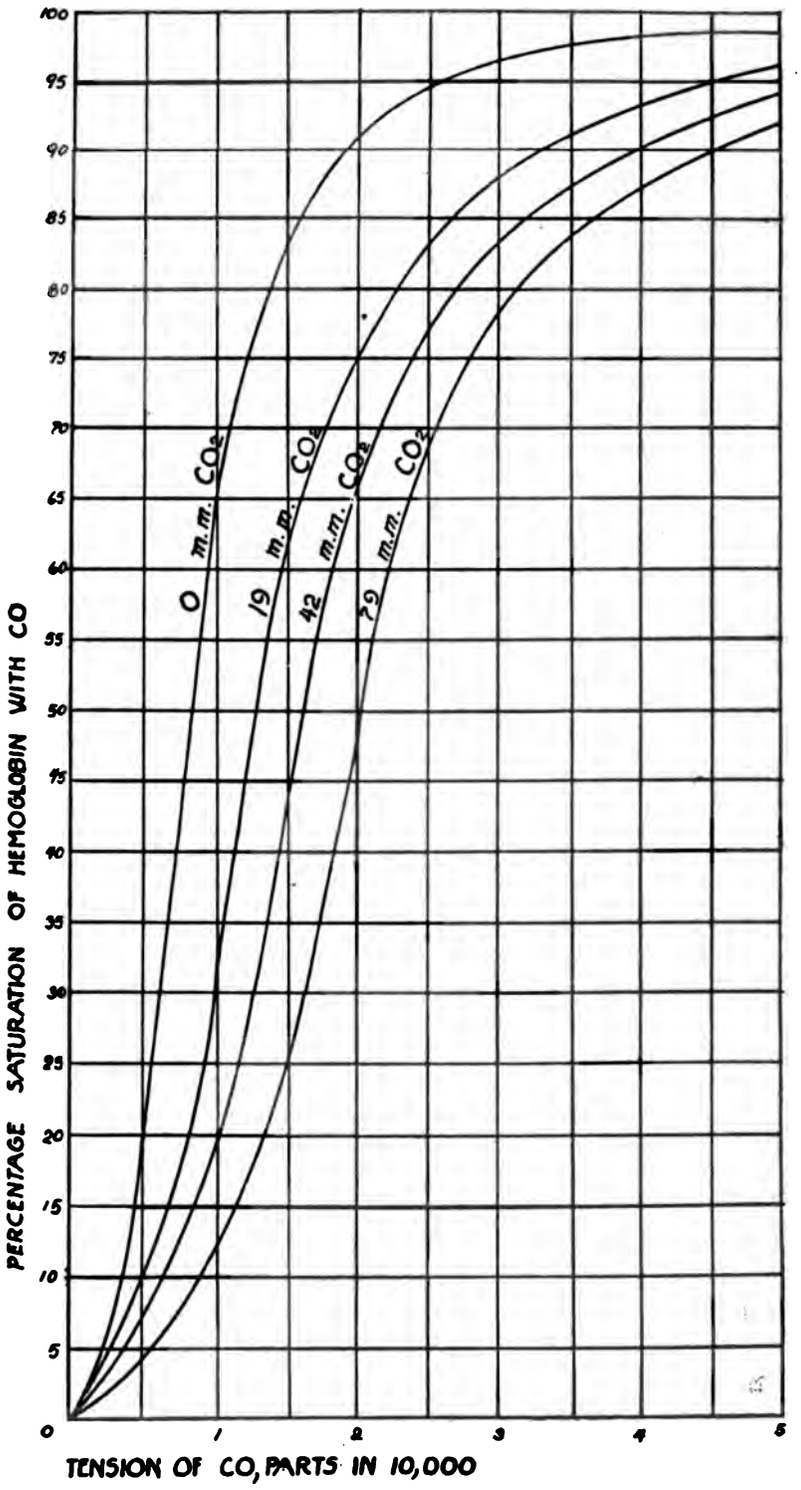
PERCENTAGE SATURATION OF HEMOGLOBIN WITH CO
TENSION OF CO, PARTS IN 10,000
0 m.m. CO2
19 m.m. CO2
42 m.m. CO2
79 m.m. CO2

Figure XVII

The equilibrated blood is then transferred to a test tube by means of a long stemmed funnel and the tube stoppered. It will be found that the equilibrated blood had a distinct pink color as compared with the yellowish red color of the unexposed standard.

4. Determination of percentage of saturation of hemoglobin with carbon monoxide.

Haldane has found that dilute carmine solution when added to dilute oxy-hemoglobin imitates exactly the tint of diluted mixtures of carbon monoxide and oxy-hemoglobin. The analytical titration is performed in two stages:

(a) By gradual addition from a burette of a standard solution of carmine to a fixed quantity of dilute oxy-hemoglobin (containing no carbon monoxide-hemoglobin) a tint corresponding to that of the partially saturated sample is attained.

(b) The addition of carmine solution is then continued until a tint is attained corresponding to that of another sample of blood solution which has been completely saturated with carbon monoxide and contains therefore 100 per cent carbon monoxide-hemoglobin. The percentage saturation of the partially saturated sample of blood solution is then calculated by simple proportion.

5. Preparation of standard carmine solution.

A stock solution of carmine is made by dissolving 0.5 gram of carmine in a few c.c. of strong ammonia solution and then diluting with distilled water to 100 c.c. The solution should be kept in a cool and dark place, as light and heat affect its color.

The standard carmine for use in the titrations is prepared by adding a few drops of the stock carmine solution to 100 c.c. of distilled water, so that the intensity of the solution slightly exceeds the intensity of color of the standard blood solution.

The diluted carmine solution is transferred to a 5 c.c. burette graduated to be read to 0.02 c.c. Another similar burette is filled with distilled water.

Four c.c. of the standard blood solution are transferred to a test tube and completely saturated with illuminating gas. This 100 per cent standard is then sealed with a rubber stopper and kept in a dark place except when in use. In another test tube, containing 4 c.c. of the standard blood solution, carmine and water are gradually added until the tint corresponds to that of the 100 per cent standard. It needs to be emphasized that tint rather than mere depth of color, is estimated by this method and therefore the determination should be made by an individual with a good sense of color.

In making the comparisons the test tubes should be held against the sky near the side of a window and the two tubes repeatedly transposed during the observation. It will be found that the contents of the tube nearest the side of the window appear deeper in intensity and pinkness. When the point of equality is reached, the transposition of the two tubes will show uniform depth and equality of color in the tube nearest the side of the window as compared with the other tube before transposition. (This is a distinctly more exact method than that afforded by any known mechanical colorimeter). Knowing the amounts of carmine solution and water required to reproduce equality of tint and intensity with the 100 per cent saturated blood, we now prepare a standard carmine solution by adding a proportionate quantity of distilled water to the (already partly diluted) carmine solution.

6. Colorimetric titration.

A narrow burette having the capacity of at least 5 c.c. and graduated in 0.02 or 0.01 c.c. is filled with the standard carmine solution. 4 c.c. of standard diluted blood are transferred to a test tube, and standard carmine solution is added to it, 0.05 c.c. at a time. After each addition the tint of the contents of the test tube is compared with the partially saturated sample which has been equilibrated with the air under examination. When the point of equality is almost reached a reading is taken from the burette. The addition of carmine solution is then continued past the point of equality until the tints again appear unequal, and the mean of the two readings is taken as the volume of the carmine required for equality of tint.

The partially saturated sample is now completely saturated with carbon monoxide by filling the upper part of the test tube with illuminating gas and shaking. The titration of the standard

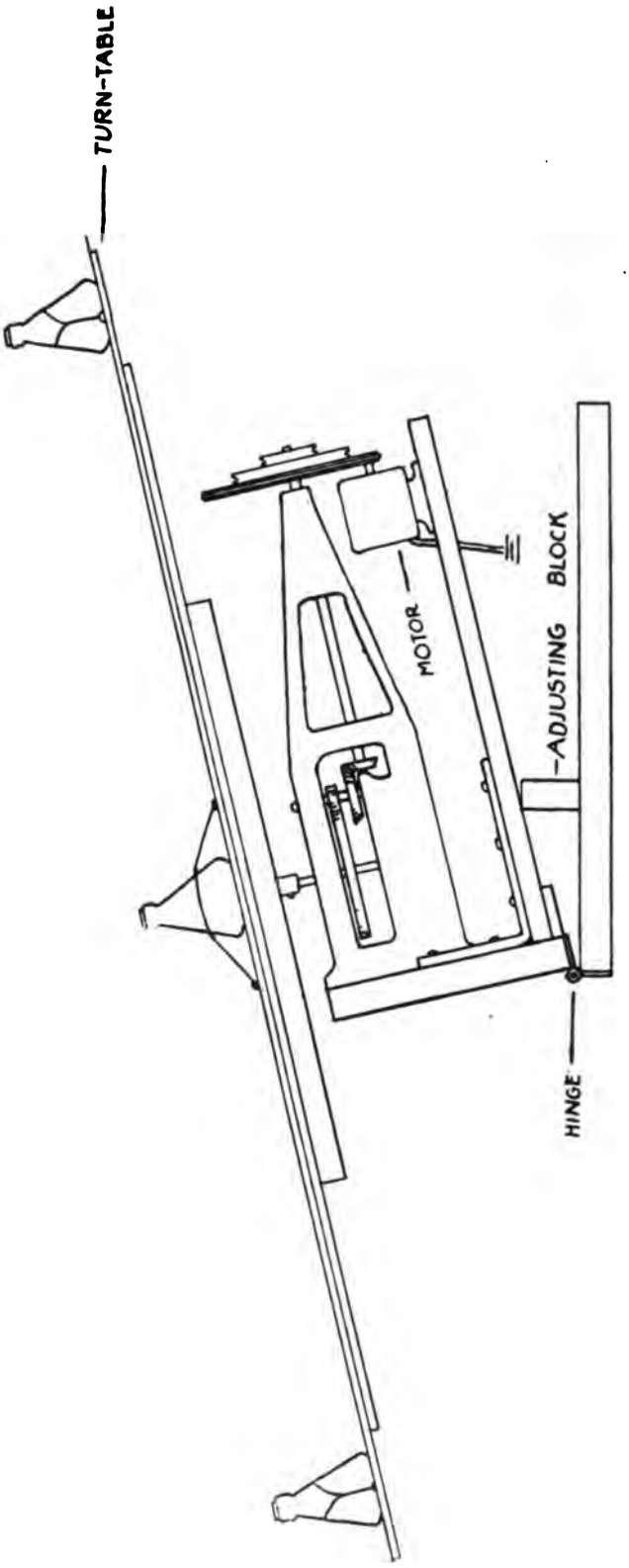

Figure XVIII

blood with carmine is then continued until the tint of the completely saturated sample is reached. The exact point of equality is obtained as the mean of two readings, as before.

Since this point of equality represents the amount of carmine solution required to imitate the 100 per cent carbon monoxide saturated blood, the percentage saturation of the partially saturated sample can be determined by simple proportion.

The following example illustrates the method of calculation. Suppose that the volumes of carmine solution used were:

For first point of equality, 0.6 c.c.
0.66 c.c. Mean 0.63 c.c.
For second point of equality, 2.8 c.c.
2.9 c.c. Mean 2.85 c.c.

As 0.63 c.c. of carmine solution was required in 0.63 plus 4 c.c. = 4.63 c. c. of the carmine oxy-hemoglobin mixture to reproduce the tint of the sample partially saturated with carbon monoxide and 2.65 c.c. of carmine were required in 2.85 plus 4 c.c. = 6.85 c.c. of the carmine oxy-hemoglobin mixture to reproduce the tint of complete saturation (100 per cent), the percentage saturation of the partially saturated sample equals x in the following:

$$\frac{0.63}{4.63} \cdot \frac{2.85}{6.85} :: x : 100 \text{ and } x = 32.7 \text{ per cent saturation.}$$

The percentage of carbon monoxide in the air with which the partially saturated sample was equilibrated can now be determined from the carbon monoxide dissociation curve of the standard blood. The curve is established beforehand once and for all by determining the percentage saturation of the blood after equilibration at room temperature with mixtures of carbon monoxide and atmospheric air of known composition. (Usually the analyst's own blood is used). The method of using the curve will be at once apparent by reference to Figure XIII. For example, if the percentage saturation of the hemoglobin with carbon monoxide at 20° C is 35 referring to the upper curve, of which one coordinate is percentage saturation of hemoglobin and the other gas tension, it will be found that the carbon monoxide in the air examined has a concentration of 3 parts in ten thousand of air.

The accuracy of the method depends in great part on the preparation of the carmine standard and the subsequent titration. With normal color sense the limit of error should not exceed three to four per cent of the actual percentage saturation of the blood.

7. The Determination of Carbon Monoxide in the Pulmonary Air of Men.

The apparatus employed by us for the collection of alveolar air will be found described in detail in Section VIII, "The Tension of Carbon Monoxide in Pulmonary Air after Gassing."

In our tests the air samples contained in the rubber bladder were analyzed for carbon monoxide by the iodine pentoxide method. The air samples in the flask were equilibrated with standard diluted blood, and the tension of carbon monoxide determined by titration with carmine.

It should be noted that the carbon monoxide dissociation curve of the standard blood is determined at an oxygen tension of 21 per cent of an atmosphere. Therefore, the tension of carbon monoxide in the pulmonary air cannot be read off directly from the curve, as the low oxygen tensions found in pulmonary air (about 14 per cent as compared with 21 per cent in outside air) distinctly increase the percentage saturation of the blood with carbon monoxide. (See Figure XVI.) In order to determine the actual tension of carbon monoxide in the pulmonary air from the percentage saturation of the standard blood after equilibration, the oxygen tension of this air must be determined by analysis. The relative affinities of carbon monoxide and oxygen for the standard blood must also be known.

The relative affinities of carbon monoxide and oxygen for the standard blood are determined for the dissociation curve of the standard blood by the formula

$$\text{Affinity CO} = \frac{T_{O_2} \times \text{CO per cent} \times \text{affinity } O_2}{(100 - \text{CO per cent}) \times T_{CO}}$$

Where T_{o_2} is the tension of O_2 (2100 when expressed in parts per 10,000 of air)

T_{co} is the tension of CO (expressed in parts of carbon monoxide in 10,000) at any given point in the carbon monoxide dissociation curve of the standard blood.

CO per cent is the percentage of saturation of the blood at a given tension of CO.

Affinity O_2 and Affinity CO are the relative affinities of O_2 and CO for the standard blood where the affinity of oxygen is 1.

For example, suppose that the standard blood equilibrated with air at six parts of carbon monoxide in ten thousand of atmospheric air, is found to be 51 per cent saturated with carbon monoxide, then

$$\frac{2100 \times 51 \times 1}{(100-51) \times 6} = 364.$$

Therefore, for this particular blood the O_2 : CO affinity ratio is 1 : 364.

Knowing the O_2 : CO affinity of the standard blood, the oxygen tension of the sample and the percentage saturation of the blood equilibrated with it, the carbon monoxide tension of the pulmonary air is obtained by the formula

$$T_{co} = \frac{\text{Per cent CO} \times T_{o_2} \times \text{Aff. } O_2}{(100-\text{Per cent CO}) \times \text{Aff. Co}}$$

For example, suppose standard blood having an O_2 : CO affinity ratio of 1 : 364 is 25 per cent saturated with carbon monoxide after equilibration with an alveolar air sample with an oxygen tension of 14 per cent of an atmosphere, then $\frac{25 \times 1400 \times 1}{(100-25) \times 364} = 1.3$ parts of carbon monoxide in 10,000 of air.

From the tension of carbon monoxide in the pulmonary air the percentage saturation of carbon monoxide in the blood in the living body of the individual tested, can be determined approximately by referring to the carbon monoxide dissociation curve and making correction for the temperature.

If equilibration of the standard blood is carried out at 20° C, multiplying the percentage saturation of the standard blood by the factor 0.92 will give the approximate percentage saturation of the blood in vivo (at 38° C).

8. The Determination of the Percentage Saturation of the Blood with carbon monoxide in Men Exposed to Air Vitiated with Carbon Monoxide.

The method of Haldane, slightly modified, was employed by us in determining the percentage saturation with carbon monoxide of the blood in vivo. Van Slyke and Salvesan (3) have recently described a method of determining the percentage of carbon monoxide in blood by means of the Van Slyke apparatus. The oxygen and carbon dioxide are set free from the hemoglobin with ferrocyanide and the oxygen and carbon dioxide absorbed in the apparatus by means of alkaline pyrogallate. The remaining carbon monoxide is then measured directly at atmospheric pressure and the necessary correction made for nitrogen dissolved in the blood. This method requires 2 c.c. of blood for each determination, and where the carbon monoxide percentage saturation of the blood is low, it is evident that 2 c.c. of blood would be insufficient. This method is probably not applicable to analysis of air for carbon monoxide. The Haldane method possesses the distinct advantage that only 20 cubic millimeters of blood are required.

Method. Before exposure to the carbon monoxide atmosphere, 20 cubic millimeters of blood are withdrawn from the finger of the subject and measured with a Gower pipette. The contents of the pipette are then diluted in a tube with exactly four c.c. of ammoniated distilled water (one part of strong ammonia to 200 parts of distilled water). The test tubes used should be of uniform caliber (ten m.m.) with a capacity of about six c.c.

Several drops of blood from the same subject are now collected in a few c.c. of ammoniated water and by the method described under 1. Method of preparation of Standard Blood (p. 195) this blood solution is diluted until it matches the test tube standard.

As four c.c. of the standard blood are required for preparing the carmine standard and for each determination, the amount of standard blood prepared will be governed by the number of determinations to be made. The standard once made should be kept in a dark cool place to prevent bleaching.

Using for comparison a sample of blood completely saturated with carbon monoxide, a standard carmine solution is prepared by the method already described. This solution should also be kept in a dark cool place.

While the man is breathing the carbon monoxide atmosphere, or soon afterward, the percentage saturation of his blood is determined by withdrawing twenty cubic millimeters of blood with a Gower pipette and diluting this blood in exactly four c.c. of ammoniated water in a test tube of the caliber given above. The tube is then closed with a rubber stopper. In collecting this sample, blowing air into the sample with the pipette or undue shaking must be avoided.

A sample of the standard blood solution is at once colorimetrically titrated with the carmine solution until a tint corresponding to that of this partially saturated sample is reached, and the first point of equality thus determined. The partially saturated sample is then fully saturated with illuminating gas and the second point of equality obtained. The carbon monoxide percentage saturation of the blood is then calculated as illustrated in Section IX.

As the partially saturated blood is collected in the ammoniated water a certain amount of dissociation of the carbon monoxide-hemoglobin occurs. For this reason the results obtained will be somewhat low; this is due in great part to the influence of oxygen present in the water.

If a 1 : 100 solution of blood is shaken with air containing carbon monoxide it will be found from the carbon monoxide dissociation curve that when the air contains about six parts of carbon monoxide in 10,000 (0.06 per cent of carbon monoxide) the blood solution is one-half saturated. Since the coefficient of absorption of carbon monoxide in water is about 0.02 at 20° C the blood solution will contain about $2 \times 0.0004 = 0.0012$ per cent of carbon monoxide in simple solution. Hence, if one-half saturated blood (containing about ten per cent of its volume of carbon monoxide) is diluted 200 times so that the dilution contains about 0.05 per cent of the volume of carbon monoxide about $\frac{0.0012 \text{ per cent}}{0.06 \text{ per cent}}$ or 2.4 per cent of the total carbon monoxide in the dilution will be required to prevent further dissociation of carbon monoxide-hemoglobin. This will cause an error of 1.2 per cent in the determination of the percentage of the carbon monoxide-hemoglobin in the blood.

Blesch has attempted to simplify the method of titration by adding to the standard blood dilution, blood which is first completely saturated with carbon monoxide and diluted to the same extent as the standard. From the quantity of fully saturated blood required to bring the standard dilution to the tint of the sample under examination the percentage saturation of the latter is determined by simple proportion. While this method does not require the preparation of a carmine standard solution it involves the possibilities of error from dissociation of carbon monoxide-hemoglobin and from combination of hemoglobin with carbon monoxide in simple solution.

With an accurately prepared carmine standard solution the error of the Haldane method, in our experience, does not exceed three per cent.

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(3) Van Slyke, D. D. and Salvarsan, H. A., J. Biol. Chem., Nov. 19, 40, No. 1, pp. 103–107.
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XI

IODINE PENTOXIDE METHOD FOR DETERMINING CARBON MONOXIDE IN LOW CONCENTRATIONS IN AIR

By M. C. Teague

Introduction:

One of the most important phases of studying the physiological effects of carbon monoxide was to find a method of accuracy and precision in determining this gas in very low concentrations. It was also desired, if possible, to apply such a method to the examination of motor exhaust gases.

The analytical determination of carbon monoxide in the concentrations here encountered (one to ten parts in 10,000 or 0.01 per cent to 0.1 per cent) offers a much more difficult problem than the usual gas determination. The Orsat method,— using active ammoniacal cuprous chloride solution as a solvent for the carbon monoxide,— does not remove the last traces of this gas; 0.2 per cent or more may not be absorbed.[1]

The apparatus (Figure XX) used for determining the purity of carbon monoxide is reliable to only about 0.02 per cent, whereas the Haldane carbon monoxide analyzer as modified by Burrell and Seibert,[2] when operated by an expert, does not exceed a precision of +0.01 per cent (one part in 10,000).

The Haldane blood method, although applicable to smaller concentrations, is subject to many variations. (For the details of this method, see the preceding section.)

The method which offered by far the greatest possibilites for determining very small amounts of carbon monoxide was that of iodine pentoxide. Briefly, this method consists of oxidizing the gas by iodine pentoxide and determining either the amount of carbon dioxide formed or that of the iodine liberated.

Considerable work has been carried out on this method since its first use by C. de la Harfe and F. Reverdin in 1888[3], Maurice Nicloux[4] absorbed the iodine in carbon bisulphide and estimated it colorimetrically. Gautier[5] assumed the reaction complete at about 65° C. He absorbed the carbon dioxide in potassium hydroxide, liberated it with sulphuric acid, and measured its volume. L. R. Kinnicutt and G. R. Sanford[6] believed the reaction complete at about 150° C. They absorbed the liberated iodine in potassium iodide and titrated it with sodium thiosulphate. E. H. Weiskoff[7] purified the iodine pentoxide first by passing through it dry air heated to 220° C. Furthermore, he found that olefin hydrocarbons, which also reduce iodine pentoxide, were completely retained by passing the gas sample through 99 per cent sulphuric acid heated to 165° C. Burrell and Seibert[8] described this method for use in determining carbon monoxide in mine gases. In their train they used acetate solution for retaining hydrogen sulphide, barium hydroxide for retaining carbon dioxide or sulphur dioxide, and both fuming and concentrated sulphuric acid for retaining any unsaturated hydrocarbons. By means of an electric furnace, they held the iodine pentoxide tube at 150° C. These investigators absorbed the carbon dioxide in baryta solution after first removing the iodine by means of potassium iodide.[9]

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[1] Burrell, G. A. and Seibert, F. M., The Sampling and Examination of Mine Gases and Natural Gas, U. S. Bureau of Mines Bulletin No. 42, p. 48.
[2] Bureau of Mines Bulletin No. 42, p. 17.
[3] Harfe, de la, C., and Reverdin, F., Chem. Zeit., Vol. 12, p. 1726.
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[5] Gautier, Armand, Compt. Rend. Vol. 126 (1898), p. 1299; Vol. 128 (1899), p. 487.
[6] Kinnicutt, L. R. and Sanford, G. R., Jour. Am. Chem. Soc., Vol. 22 (1900), p. 14.
[7] Weiskoff, E. H., Jour. Chem. Met. Min. Soc., South Africa, Vol. 9 (1909), p. 258.
[8] Burrell, G. A. and Seibert, F. M., Bureau of Mines Bulletin No. 42 (1913), p. 60.
[9] It would be expected that the solution of the carbon dioxide in the KI solution might cause slightly low values or the incomplete absorption of the iodine to cause correspondingly high values. A straight tube absorber was used for the iodine and one Fresenius nitrogen flask to catch the carbon dioxide

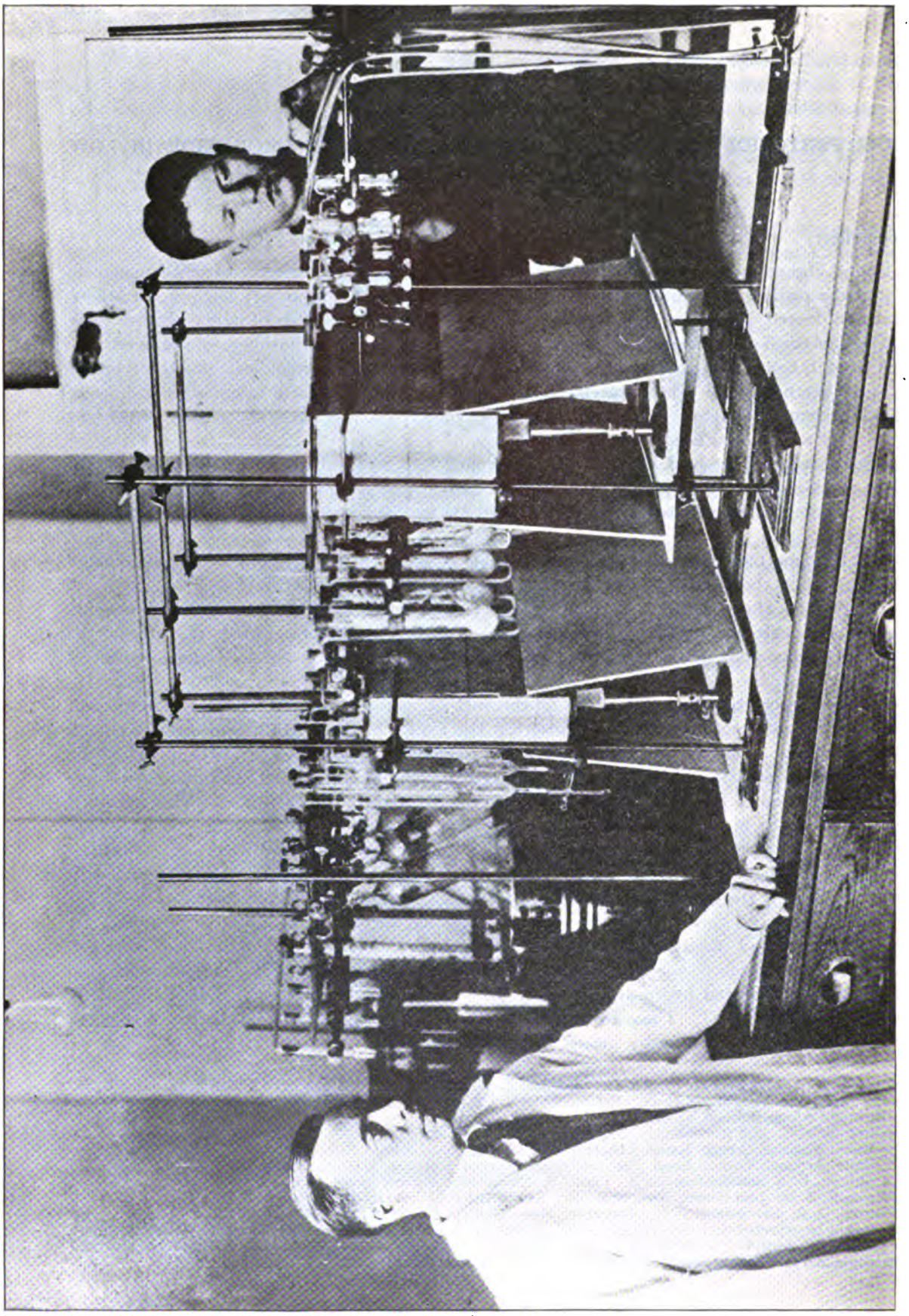

Figure XIX

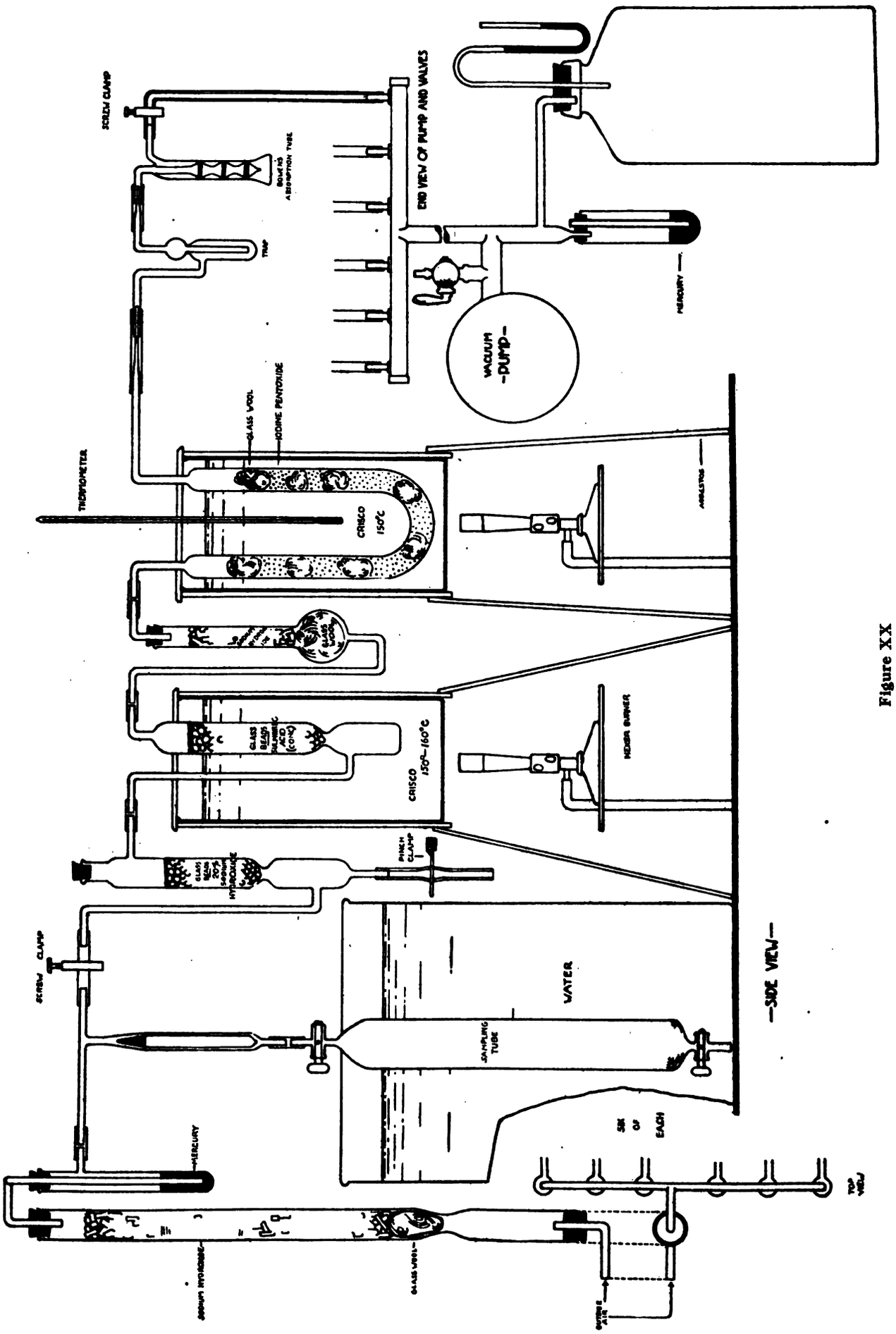
SCREW CLAMP
TRAP
END VIEW OF PUMP AND VALVES
MERCURY
VACUUM PUMP
GLASS WOOL
IODINE PENTOXIDE
THERMOMETER
CRISCO 150°C
ASBESTOS
CRISCO 150-160°C
BUNSEN BURNER
PINCH CLAMP
WATER
SAMPLING TUBE
—SIDE VIEW—
SIX OF EACH
TOP VIEW
MERCURY
GLASS WOOL

Figure XX

A portable iodine pentoxide apparatus has been described by J. Ivon Graham.[10] He makes use of bromine in potassium bromide solution to remove any unsaturated hydrocarbons, and dries the gas with calcium chloride and then phosphorous pentoxide before it enters the iodine pentoxide tube. The latter is held at temperatures between 90° C. and 150° C., there being observed no difference in results over this range except in the presence of relatively large amounts of hydrogen. One and two hundred c.c. samples were taken and the liberated iodine determined by titration. Under careful controlled conditions, an accuracy is claimed to within 0.5 part carbon monoxide in 10,000 parts of gas (or 0.005 per cent carbon monoxide). (It is stated that the experimental error of the titration alone may easily amount to 0.005 per cent.)

Experiments are quoted by Graham to show that the presence of relatively large amounts of hydrogen (up to twenty per cent) causes an error which, estimated as carbon monoxide, is equivalent to as much as 0.02 per cent for a 100 c.c. sample. This effect varies directly with the temperature and time of exposure to the iodine pentoxide. (A temperature of 90°—130° is recommended.)

In connection with the work on carbon monoxide absorbents for gas masks Lt. Col. A. B. Lamb[11] and his coworkers used the iodine pentoxide method. At that time, there was developed by A. T. Larson and E. C. White[12] a multiple apparatus practically the same as the Type 1 herein later described. Their attempted accuracy was 0.01 per cent carbon monoxide. They also found an interference by hydrogen.

Iodine Pentoxide Methods as Employed In the Tunnel Gas Investigations.

Upon first inspection of the equation

$$I_2O_5 + 5CO \rightarrow 5CO_2 + 2I$$

it would seem most advantageous to determine the carbon dioxide, since there is a relatively large amount of it formed. At these very low concentrations, however, the complete absorption of carbon dioxide is an exceedingly difficult operation. For most types of absorption tubes there would be the inconvenience of using several such tubes or of passing the gas through the apparatus at a slower rate. Furthermore, we have found it undesirable to work with baryta solution much weaker than 0.02 Normal, whereas in determining the iodine liberated by the reaction, 0.001 Normal sodium thiosulphate can be used. This difference offsets the advantage of the greater amount of carbon dioxide formed.

Apparatus: Type 1.

This apparatus is shown diagrammatically in Figure XX. The sample of gas is passed successively through (a) a bead tower containing twenty per cent sodium hydroxide, (b) a bead tower containing concentrated sulphuric acid (sp. gr. 1.84), which is maintained at approximately 160° C., (c) a tube containing solid sodium hydroxide, then (d) the iodine pentoxide tube, which is protected by a guard tube before the absorption bulb. The carbon dioxide in the sample is sufficiently removed by the alkali. In view of applying the method to exhaust gases, the concentrated sulphuric acid is heated to approximately 160° C. to remove any unsaturated hydrocarbons present.[13] For the carbon monoxide — air mixtures, the concentrated sulphuric acid is needed to dry the gas before it passes into the iodine pentoxide tube. Moisture renders the method less sensitive, and therefore the acid should be renewed before it becomes very dilute. The tube containing solid sodium hydroxide retains the fumes from the hot acid and also serves as a guard before the iodine pentoxide tube. The latter is held at 150° C. although for the gas mixtures here used the temperature is not a sensitive factor. One Bowen's absorption tube containing a ten per cent potassium iodide solution has been found efficient in absorbing the liberated iodine.

[10] Graham, J. Ivon, The Accurate Determination of Carbon Monoxide in Gas Mixtures, Jour. of Soc. of Chem. Industry, Vol. 38 (1918), p. 10.

[11] In charge of the Defence Research Section, G. W. S., U. S. A.

[12] We wish here to express our appreciation for the use of unpublished data relative to Larson and White's iodine pentoxide apparatus.

[13] Weiskoff, E. H., Hour, Chem. Met. Min. Soc., South Africa, Vol. 9 (1909), p. 258.

The sodium thiosulphate solution is made of such a strength (0.002387 N) that one cubic centimeter is equivalent to 0.15 c.c. of carbon monoxide, or 1.5 parts in 10,000, when a liter sample of gas is used.

The safety valve which is used for automatically closing the sampling bulb and opening the outside air tube was devised by Mr. E. C. White, of the Defense Research Section, C. W. S.

The iodine pentoxide tubes are made of about three-quarter inch Pyrex tubing and the U about ten inches long. They are filled with alternate layers of glass wool and iodine pentoxide (each tube containing thirty to forty grams of iodine pentoxide). The arm on the exit side from the U-tube is somewhat longer than the other, and is tapered to make an interlocking glass joint with the guard tube. A similar joint is made with the absorption bulb, thus removing the possibility of error due to rubber connections.

After assembling the apparatus, the iodine pentoxide must be conditional before making any determinations. This is accomplished by raising the temperature to 220°–230° C. for several hours while air is drawn through. Iodic acid decomposes at about 170° C. to form water and iodine pentoxide. With the water, considerable iodine is at first drawn off. Two varieties of iodine pentoxide were tried;— one, the ordinary commercial variety, prepared by the oxidation of iodine with fuming nitric acid, required about 25 hours heating at first; while the other variety, prepared by one chloric acid method[14], required only about fifteen hours heating. The tubes containing the latter variety gave lower blanks, and seemed more active and therefore less sensitive to temperature changes than did the other tubes.

For the first determinations, the blanks (on chloric acid method iodine pentoxide) were about 0.2 c.c. of the above thiosulphate solution when two liters of air has been passed through the apparatus. They soon diminished, however, to almost zero for the same length run. Later, the sample and sweeping of the train were extended to one hour (using the rate of one liter for fifteen minutes), and the blanks for this time varied from 0.1 to 0.2 c.c. of the thiosulphate. When desiring great precision, it is advisable to redetermine the blank each day.

In order to determine the necessity of removing possible small traces of carbon monoxide from the outside air which was used for sweeping out the apparatus, the following experiment was carried out: Air was drawn slowly through a hot combustion tube containing copper oxide and collected in a large bottle. Blanks determined upon this air were the same as those obtained from the outside air.

Much time was saved by the construction of a six unit multiple apparatus. (See Figure XX).

Method of Preparing the Carbon Monoxide-Air Mixtures:

For investigating the influence of such factors as the temperature, rate of flow, etc., the following convenient procedure was used in making up the carbon monoxide-air mixtures. Almost pure carbon monoxide was generated by the action of concentrated sulphuric acid on strong formic acid. A measured amount of this gas was then withdrawn by means of a ten or twenty c.c. all glass Luer syringe and injected into the inlet rubber tubing of a calibrated twenty liter carboy, and through which water was flowing from an over-flow funnel. By injecting the needle into the rubber tubing at a small angle, as described by Henderson and Smith,[15] the rubber, together with the water seals the hole after the operation. Thus the gas is seen to enter the bottom of the carboy. The flow of water is now stopped and the vessel shaken at intervals for a few minutes, (the presence of the small amount of water in the bottle facilitates the mixing). To draw the samples, the outlet rubber tubing is well cleared and then connected to the sampling bulb, which is first filled with water. Water constantly flows into the carboy as the gas is drawn out. In this manner, twenty liters of the mixture of any concentration of carbon monoxide from 0.01 per cent to 0.10 per cent (our entire range) can be made within a few minutes. In case a considerable degree of accur-

[14] This method will be described later by A. B. Lamb and W. C. Bray.
[15] Henderson, Y. and Smith, A. H., Journal of Biological Chemistry, 1918, XXXIII, 39.

acy is desired, the purity of the carbon monoxide is first determined by a previously described apparatus (Figure IV).

Procedure:

As stated above, the blanks were determined each day by drawing outside air through the apparatus for the same length of time as used for the determinations. In most cases, one liter samples were passed through the apparatus and the train then cleared with outside air. The iodine was titrated with the thiosulphate, the blank deducted, the titration corrected to that of an exactly one liter sample, and multiplied by 1.5 (thiosulphate factor) to obtain the parts of carbon monoxide in 10,000 of air.[16] (Hereafter in this report, all concentrations will be referred to in terms of parts of carbon monoxide in 10,000 of air.)

Results:

(1) *Effect of Temperature:*

In the following determinations, the samples were drawn through in about fifteen minutes and then outside air drawn through for the same length of time. The temperature of the I_2O_5 tube was varied.

TABLE I

	Parts CO in 10,000	
Temperature	100° C.	150° C.
	1.74	1.79
	4.91	4.87
	4.87	4.76

TABLE II

	Parts CO in 10,000		
Temperature	100° C.	150° C.	175° C.
	5.98	6.05	5.72
	5.55	5.69	5.67
	5.43	5.67	5.44
	5.75	5.92	5.69
	5.81	5.95	5.70
	6.15	6.18	6.14
Mean	5.78	5.91	5.73

(2) *Variations of the Precision with the Rate and Time of Sweeping the Train:*

In Table III are shown the results of determinations differing only in the rate and time used for sweeping the apparatus clear. Unless otherwise stated, the rate of flow is fifteen minutes per liter.

[16] A weaker solution could probably be used, so that 1 cc. thiosulphate would be equivalent to 1 part carbon monoxide in 10,000 for a liter sample.

TABLE III

SERIES NUMBER	Procedure	Sample Number	Parts CO Found	Parts CO Mean	Maximum Variation from Mean
I	Total time, 30 minutes (15 minutes for sample and 15 minutes for clearing train).	1	2.03		
		2	1.84		
		3	1.32		
		4	1.81	1.71	+—0.40
		5	1.55		
		6	1.69		
IA		1	8.35		
		2	8.51		
		3	8.94	8.77	+—0.40
		4	8.91		
		5	8.84		
		6	9.04		
II	Total time, 45 minutes (15 minutes for sample and 30 minutes for clearing train).	1	4.26		
		2	4.12		
		3	4.09	4.11	+—0.16
		4	4.11		
		5	4.14		
		6	3.95		
IIA		1	5.53		
		2	5.52		
		3	5.35		
		4	5.47		
		5	5.44		
		6	5.53	5.48	+—0.13
		7	5.47		
		8	5.47		
		9	5.35		
		10	5.61		
		11	5.46		
		12	5.50		
III	Total time, 60 minutes (15 minutes for sample and 45 minutes for clearing train).	1	2.53		
		2	2.60		
		3	2.84	2.64	+—0.20
		4	2.53		
		5	2.54		
		6	2.81		
IIIA		1	1.27		
		2	1.18		
		3	1.27	1.20	+—0.08
		4	1.18		
		5	1.12		
IIIB		1	4.88		
		2	4.90		
		3	4.68	4.88	+—0.20
		4	5.01		
		5	4.74		
		6	5.07		

TABLE III—(*Concluded*)

SERIES NUMBER	Procedure	Sample Number	Parts CO Found	Parts CO Mean	Maximum Variation from Mean
IV	Total time, 60 minutes (30 minutes for sample and 30 minutes for clearing apparatus).	1	5.80		
		2	5.47		
		3	5.30	5.53	+—0.27
		4	5.47		
		5	5.64		
		6	5.47		
IV-A		1	4.60		
		2	4.45		
		3	4.40	4.47	+—0.13
		4	4.43		
		5	4.54		
		6	4.40		
V	Total time, 75 minutes (15 minutes for sample and 60 minutes for clearing train).	1	4.09		
		2	3.97		
		3	3.90	4.00	+—0.10
		4	4.04		
		5	3.93		
		6	4.05		

SUMMARY TABULATION

SERIES NUMBER	Procedure	Number of Determinations	Parts CO Mean Value	Maximum Variation from Mean (Parts CO)
I	Total time, 30 minutes (15 minutes for sample and 15 minutes for sweeping the train)	6	1.71	+—0.40
I-A		6	8.77	+—0.40
II	Total time, 45 minutes (15 minutes for sample and 30 minutes for sweeping the train)	6	4.11	+—0.16
II-A		12	5.48	+—0.13
III	Total time, 60 minutes (15 minutes for sample and 45 minutes for sweeping the train)	6	2.64	+—0.20
III-A		5	1.20	+—0.08
III-B		6	4.88	+—0.20
IV	Total time, 60 minutes (30 minutes for the (1 liter) sample and 30 minutes (2 liters) for sweeping the train)	6	5.53	+—0.27
IV-A		6	4.47	+—0.13
V	Total time, 75 minutes (15 minutes for sample and 60 minutes for sweeping the train)	6	4.00	+—0.10

From the above results it is apparent that the temperature of the iodine pentoxide tube is not a sensitive factor when working with carbon monoxide-air mixtures. There are no observed differences in the results when temperatures of 100°, 150° and 175° C, were used. (The iodine pentoxide in these tubes was prepared by the chloric acid method.)[17] A temperature of 150° C. was used for all the determinations of this investigation.

When working with the above carbon monoxide concentrations, the most desirable rate of flow was found to be approximately 60 c.c. per minute, or a liter in fifteen to seventeen minutes. If a precision of only ±0.40 part carbon monoxide is desired, the train need be swept only fifteen minutes; whereas by drawing outside air through for an hour after each sample, the precision will be increased to about ±0.1 part.

For the early results obtained in this investigation, the liter samples were drawn through in about fifteen minutes and the train swept out for the same length of time. Later, when greater precision was desired, fresh air was drawn through the apparatus for forty-five minutes after each sample.

APPLICATION TO CARBON MONOXIDE DETERMINATION IN EXHAUST GAS

From the nature and purpose of the investigation, it was desirable to apply the above method of determining carbon monoxide to dilute motor exhaust gases. Analyses of these mixtures have shown the following constituents to be present: Carbon dioxide, carbon monoxide, oxygen, hydrogen, methane, and perhaps other low saturated hydrocarbons, traces of unsaturated hydrocarbons, and some unburned gasoline.[18] Obviously enough there are also varying amounts of oil smoke particles.

Carbon dioxide is sufficiently removed by a head tower containing a twenty per cent solution of sodium hydroxide.

Any traces of unsaturated hydrocarbons are absorbed in the bead tower of concentrated sulphuric acid (sp. gr. 1.84) heated to about 160° C.

As noted above, several investigators have found hydrogen to be partly oxidized by the hot iodine pentoxide. In each case, however, the amount of hydrogen was relatively large. In exhaust gases, the hydrogen content varies up to about one-half that of carbon monoxide;— the effect of such low concentrations had, therefore, to be determined.

While methane and ethane do not interfere with the iodine pentoxide reaction, Graham observed that normal pentane was slightly affected at the temperaures used (90°–150° C.). If that is true, it was to be expected that gasoline (hexane and heptane) would undergo oxidation even more readily.

There were, therefore, three possible sources of difficulty in applying the above described iodine pentoxide apparatus to the determination of carbon monoxide in exhaust gases,— namely, the presence of hydrogen, smoke particles and gasoline vapor.

1 — *Experiments on Exhaust Gas:*

A number of experiments were made to check up the methods of analyses and of obtaining desired concentrations in the gassing chamber. The following is the tabulation of results:—

[17] With the presence of considerable quantities of hydrogen, its least effect would be observed at the lowest temperature.

[18] Analyses made at the Pittsburgh Station, Bureau of Mines.

TABLE IV

Experiment Number	Method of Determining CO Concentration	Calculated CO Concentration	CO found in I_2O_5 Method	Ratio I_2O_5 Value Calculated Value
1	CO from formic acid (not analyzed).	In gassing chamber, 1.98 parts	1.82	0.92
2	95% CO by Henderson analyzer	In gassing chamber, 3.9	3.86	1.00
3	Exhaust gas, Orsat determination, 6.7% CO	In gassing chamber, 3.0	3.90	1.30
4	Exhaust gas, Orsat determination, 6.5% CO	In gassing chamber approximately 2.8	3.50	1.25
5	Exhaust gas, Orsat determination, 8.4% CO	In gassing chamber 1.0	1.34	1.34
6	Exhaust gas, Orsat determination	In gassing chamber, 13.5	17.8	1.32
7	Exhaust gas, Orsat determination, 6.3% CO	Orsat burette to sampling tube and then diluted to 1 liter, 10.29	13.77	1.34
8	Exhaust gas, 6.3% CO	Orsat burette to sampling tube and then diluted to 1 liter, 9.59	13.62	1.42

In experiments 1 and 2, the pure carbon monoxide was measured in a graduated cylinder and displaced by water. In others using the gassing chamber, the exhaust gas was displaced from a large graduated gasometer. In the last two experiments, the exhaust gas was measured out of the Orsat burette directly into the sampling tube, and then diluted to approximately one liter.

The following points are to be noted:

When pure carbon monoxide is used, the calculated chamber concentration is probably accurate to $\pm$ ten per cent of that actually given by the analyses. Nevertheless, when exhaust gas is used, consistently higher results are obtained by the iodine pentoxide method. This increase is the same for two different methods of dilution, but varies when using gas from different cars. The above results show an increase of about thirty-five per cent obtained when using gas from a six cylinder Overland car (idling at same speed and carburetor adjustment). A Ford car in poor condition showed similar results, but with an increase of sixty to eighty per cent. While it is true that the cuprous chloride solution of the Orsat apparatus does not absorb the last traces of carbon monoxide, that not absorbed can by no means account for the observed high results. It is evident that some one or more constituents of the exhaust gas are also being oxidized by the iodine pentoxide.

2 — *Effect of Hydrogen:*

Mixtures of carbon monoxide and air were prepared as previously described. From these, samples were withdrawn, a known volume of hydrogen injected in the remaining gas and then additional samples taken.

Experiment A (Added one-half as much hydrogen as carbon monoxide).

CO–Air Mixture — Parts CO

	Without Hydrogen	With Hydrogen	
Temperature	150°	150°	100°
	1.58	1.76	1.74
	1.67	1.68	.....
Mean	1.63	1.75	1.74

Experiment B (Added hydrogen = one-half and one times carbon monoxide volume.)

CO–Air Mixture — Parts CO

	Without Hydrogen	With Hydrogen = ½ volume	With Same Volume Hydrogen as CO	
Temperature	150° C.	150°	100°	150°
	4.67	4.76	4.91	4.91
	4.79	4.87	4.87	.....
Mean	4.73	4.81	4.89	4.91

Experiment C (Temperature 150° C).

PARTS CO I_2O_5 METHOD

Series I Without Hydrogen	Series II 1.2 parts CO and Approximately 2.2 Parts Hydrogen	Series III 1.2 parts CO and Approximately 4.5 Parts Hydrogen
1.27	1.47	1.88
1.16	1.47	1.47
1.27	1.62	1.47
1.18	1.72	1.84
1.14	1.64	1.89
		1.89
Mean 1.20	1.58	1.74

These experiments justify the conclusion that such quantities of hydrogen as occur in exhaust gases (about one-half the carbon monoxide concentration) are not sufficient at these low concentrations to influence the carbon monoxide determinations as obtained by the iodine pentoxide method. It is not until the hydrogen is present in about twice the volume of carbon monoxide that any effect is observed in the above determinations, and even then the results are not conclusive.

3. *Effect of Smoke Particles from the Oil:*

Although a pad of glass wool was used in the soidum hydroxide tube just before the iodine pentoxide, it was possible for small smoke particles to pass through this and perhaps increase the iodine liberated. To determine whether or not this caused the observed high results from exhaust gas, a paper filter was inserted into the train. The filter was made by clamping two eleven centimeter quantitative filter papers of good quality between two ground edge funnels, permitting a filtering area of about ninety square centimeters.

The use of this filter was found to make no difference in the determinations on exhaust gas; i. e., the iodine pentoxide carbon monoxide determinations were the same as these when the filter was not used, (sixty per cent to eighty per cent higher than the value calculated from the Orsat analysis).

4. *Effect of Gasoline:*

There still remained the possibility that the small amounts of unburned gasoline was interfering.

Experiment A:

A mixture was prepared of carbon monoxide and air; three samples taken; hydrogen was added to about one-half the carbon monoxide concentration, and three more samples drawn; and finally 0.5 c.c. of liquid gasoline was injected, and after thorough shaking, three samples taken of this mixture. All determinations were made with the iodine pentoxide tube at 150° C.

PARTS CO OR EQUIVALENT

	CO	CO+M_2	CO+H^2 Gasoline
1	3.85	3.78	44.4
2	3.53	3.29	42.1
3	3.72	3.66	49.4
Mean	3.70	3.60	45.3

Experiment B:

A similar mixture of carbon monoxide and air was prepared, containing about four parts of carbon monoxide. Three samples were taken. Motor gasoline vapor was placed in an Erlenmeyer flask and stoppered. The temperature of the flask was raised to thirty-five degrees or forty degrees by placing it in warm water. After standing for several hours and again brought to room temperature, the calculated *volume* of the flask atmosphere to make about 1 c.c. of pure gasoline vapor in ten liters of air was withdrawn by a needle and inserted into the above carbon monoxide-air mixture. Two samples were drawn of this mixture, and the carbon monoxide equivalent determined on the same apparatus as used above.

PARTS CO OR EQUIVALENT

	CO	CO+ Gasoline
1	4.11	6.98
2	4.26	7.19
3	4.01	.....
Mean	4.13	7.08

It is quite evident from the above experiments that, whereas the concentrations encountered of hydrogen and some particles do not interfere in the I_2O_5 method of determining carbon monoxide in exhaust gases, the unburned gasoline vapor interferes to a considerable extent.

Several absorbents were tried for the removal of gasoline vapor without affecting the carbon monoxide concentration.

(A) *Cold concentrated sulphuric acid* inserted in the train before the heated acid had no effect upon the results.

RESULTS OF EXPERIMENTS WITH ACTIVATED CHARCOAL

(1) *Using Exhaust Gas:*

NUMBER	CO Content of Exhaust Gas (Orsat) Per cent	Exhaust Gas Taken from Orsat Burette c.c.	Corresponding Parts CO Taken	CORRESPONDING PARTS CO FOUND BY I_2O_5 METHOD			
				Usual Apparatus	Usual Apparatus with Charcoal in Train	Ratio I_2O_5 value Orsat Value	Mean Ratio
1	6.8	8.65	5.88	8.41	.....	1.43	1.35
2	6.8	8.50	5.78	7.37	.....	1.28	
3	6.8	8.52	5.79	.....	6.55	1.13	1.04
4	6.8	8.07	5.49	.....	5.17	0.94	
5	6.8	8.71	5.92	.....	6.46	1.09	
6	3.1	16.26	5.04	.....	5.71	1.13	1.06
7	3.1	15.48	4.80	.....	5.00	1.04	
8	3.1	16.30	5.05	.....	5.17	1.02	

(B) Dry activated cocoanut charcoal was known to be a good absorbent for gasoline vapo- and at the same time useless for absorbing carbon monoxide. A tube of this absorbent was therer fore inserted before the I_2O_5 tube in the place of the solid sodium hydroxide. With this arrangement, the high results on exhaust gas were reduced to very nearly the calculated value. When determinations were made, however, on carbon monoxide-air mixtures, the carbon monoxide was found to be appreciably absorbed by the charcoal.

(2) *Using Carbon Monoxide-Air Mixture*

PARTS CO

NUMBER	Usual Apparatus	Usual Apparatus with Charcoal in Train as Above
1	6.09	4.38
2	5.89	3.83
3	5.71	3.98
4	.....	4.15
Mean	5.90	4.08

(C) Many *heavy mineral oils* were also good absorbents of gasoline vapor at higher concentrations. A bead tower containing such an oil (Albolene) was therefore inserted in the train in front of the sulphuric acid tower. It was found that the vapor pressure of this oil was sufficiently high to cause an undesirable blank, due to the reaction with the I_2O_5. The normal 2 liter (30 minutes) blank was determined as 0.1 c.c. of the thiosulphate (0.0025, N.). After inserting the oil tower, the blank at room temperature was found to be 3.90 and 4.60 c.c. When the oil tower was surrounded by an ice bath, the blank was reduced to 2.88 and 1.32 c.c. (The oil is a solid at

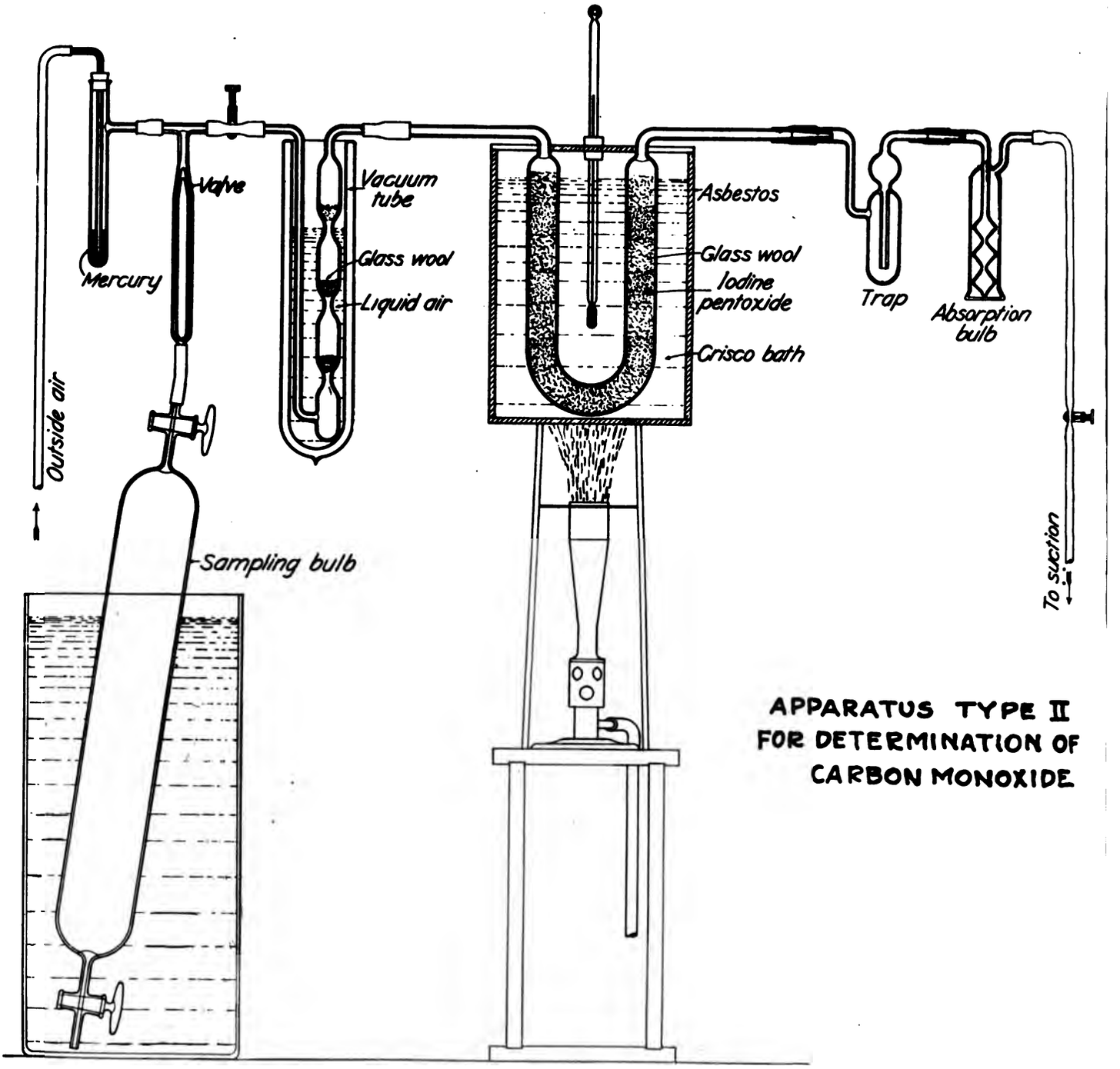
Valve
Vacuum tube
Asbestos
Glass wool
Glass wool
Iodine pentoxide
Trap
Absorption bulb
Mercury
Liquid air
Crisco bath
Outside air
Sampling bulb
To suction
APPARATUS TYPE II
FOR DETERMINATION OF
CARBON MONOXIDE

Figure XXI

80° C.) A somewhat variable blank of this magnitude would introduce an appreciable error, even though it removed completely the gasoline vapor in the exhaust gas.

(D) Shaved *paraffin* was found to have no effect upon the results, either with exhaust gas or carbon monoxide-air mixtures. The average of three determinations on exhaust gas using the usual train showed an increase of seventy-four per cent over the calculated carbon monoxide value, whereas with the paraffin in the train, an average of the same number of determinations showed an increase of seventy per cent. On the two procedures with carbon monoxide-air mixtures, the determinations checked.

(E) It was thought possible that by chilling the dried entering gases to —80° C., the gasoline would be condensed to droplets capable of being filtered out. The gas was led through a small U-tube containing glass wool, and about which was packed carbon dioxide snow. With the failure of this to give the desired result, the tube containing the glass wool was replaced by one containing an allundum cylinder (Norton, medium porosity). The chilled gas was then drawn through this porous cup. The results on exhaust gas were still unaffected.

(F) The next lower convenient temperature was that of *liquid air*. A similar U-tube containing glass wool was employed. While liquid gasoline cooled to this temperature (—190° C.) becomes a glass-like solid it was realized that its vapor at such exceedingly low partial pressures might still prove difficult to completely remove.

Results: A twenty liter carbon monoxide-air mixture was prepared; three samples withdrawn; air containing gasoline vapor was injected into the remainder and six samples taken. The carbon monoxide values of three of the latter samples were determined on the apparatus previously used and three on the train with the liquid air cooled tube.

CO + Air Mixtures Old Apparatus Parts CO	CO + Gasoline + Air Old Apparatus Parts CO Equivalent	CO + Gasoline + Air "liquid air tube" in Train Parts CO Equivalent
8.3	48.0	7.8
8.0	46.7	7.6
7.5	46.0	7.8
Mean 7.9	46.9	7.7

Thus, at this temperature, the gasoline vapor was completely removed even under greatly exaggerated conditions.

The liquid air temperature also condensed the water, carbon dioxide and probably all of the unsaturated hydrocarbons. All of the members of the former purifying train were therefore removed leaving only the liquid air cooled tube (Type II apparatus). Repeated determinations showed the same results.

Carbon Monoxide-Air Mixtures

	Type I Apparatus Parts CO	Type II Apparatus Parts CO
	5.8	5.2
	5.9	5.7
	5.7	5.4
	4.9	5.0
Mean	5.6	5.3
	16.1	16.4
	16.2	16.3
Mean	16.2	16.4

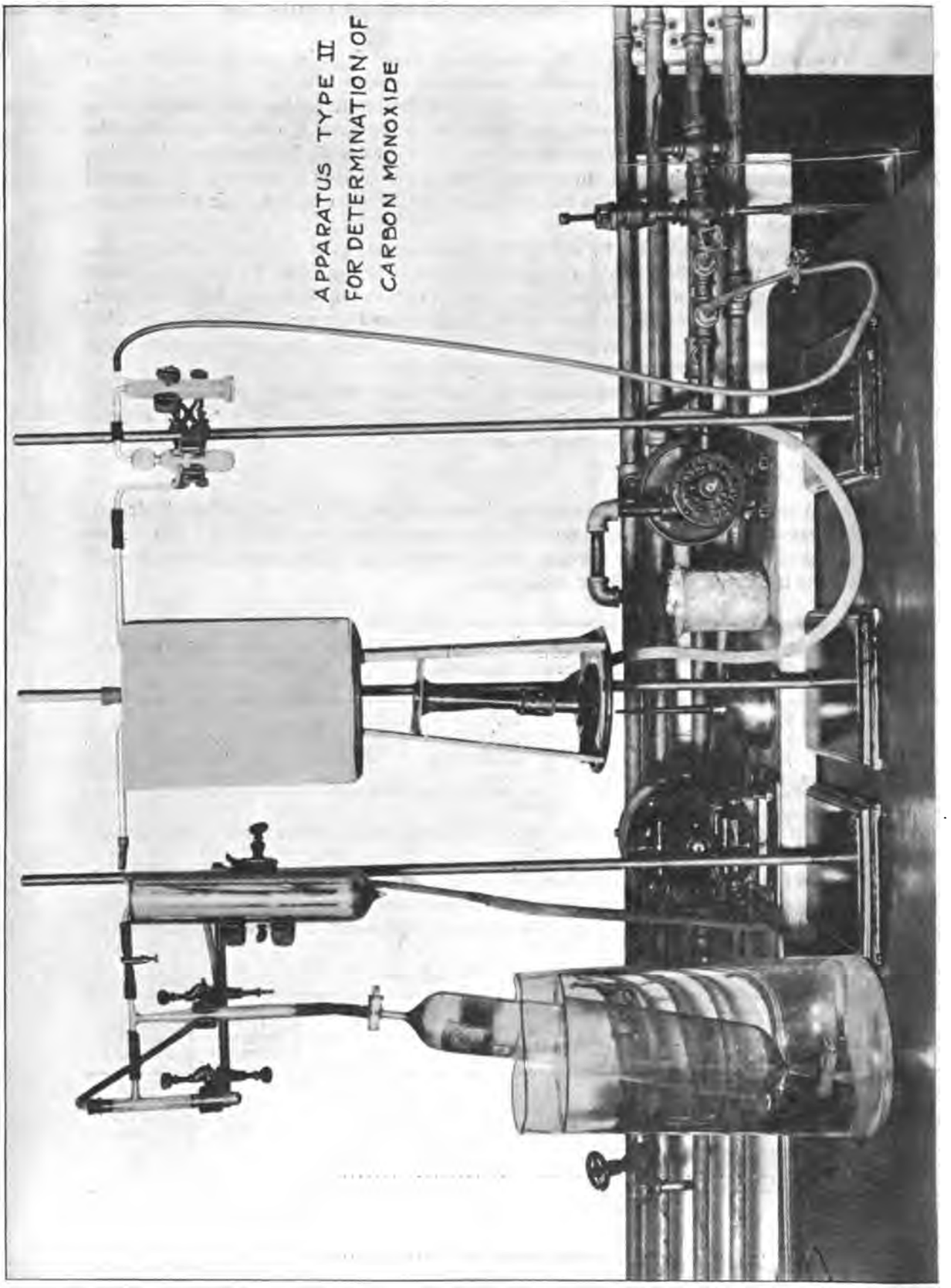

Figure XXII

In the following tables are found the results of numerous determinations on exhaust gases.

Exhaust Gas Containing 3.8% CO from Machine in Apparently Good Condition

Measured from Gas Burette c.c.'s CO Taken	Type I Apparatus		Type II Apparatus	
	c.c.'s CO found	Per cent of calculated	c.c.'s CO found	Per cent of calculated
1.16	.....	.....	1.12	97
1.05	.....	.....	1.08	103
0.80	0.87	111	.....	.....

Exhaust gas containing 4.0 % CO from Army truck with one cylinder not functioning

Measured from Gas Burette c.c.'s CO Taken	Type I Apparatus		Type II Apparatus	
	c.c.'s CO found	Per cent of calculated	c.c.'s CO found	Per cent of calculated
0.99	.....	.....	1.06	107
1.04	1.73	166	.....	.....
.63	.....	.....	.59	94
.57	0.94	170	.....	.....
.65	.....	.....	.64	99
.64	1.03	161	.....	.....
Mean	.....	166	.....	100

Exhaust Gas containing 9.6% of CO from Army truck (Engine Racing)

Measured from Gas Burette c.c.'s CO Taken	Type II Apparatius	
	c.c.'s CO found	Per cent of calculated
0.78	1.79	101
1.03	1.04	101
1.16	1.19	103
Mean	.....	102

From the results it is noted that at liquid air temperature all of the gases in exhaust gas are removed which interfere with the accurate carbon monoxide determination by the I_2O_5 method.

In apparatus type II the Dewar vacuus tube has replaced four members of the type I purifying train. This simplified apparatus will probably reduce the time per determination by fifty per cent due to the shorter time necessary to completely clear the train. The elimination of liquid seals

NE	Fredk L. Cranford Inc. 149 Remsen St. Brooklyn.		Rogers & Haggerty 103 E. 125th St New York		Engineer's Estimate.	
ITE	PRICE	AMOUNT	PRICE	AMOUNT	PRICE	AMOUNT
1	$ 15.00	$ 4950.00	$ 20.00	$ 6600.00	10.00	3300.00
2	15.00	15450.00	20.00	20600.00	10.00	10300.00
3	15.00	12600.00	25.00	21000.00	12.00	10080.00
4	55.00	47850.00	20.00	17400.00	10.00	8700.00
5	55.00	458150.00	69.00	574770.00	23.00	191590.00
6	15.00	150.00	60.00	600.00	30.00	300.00
27	20.00	14500.00	30.00	21750.00	22.00	15950.00
27-L	20.00	54200.00	30.00	81300.00	16.00	43360.00
28	30.00	23100.00	40.00	30800.00	26.00	20020.00
29	10.00	3000.00	10.00	3000.00	6.00	1800.00
34	50.00	250.00	50.00	250.00	40.00	200.00
45	10.00	100.00	15.00	150.00	7.00	70.00
46	10.00	100.00	15.00	150.00	7.00	70.00
47	10.00	10000.00	20.00	20000.00	10.00	10000.00
48	10.00	1000.00	20.00	2000.00	10.00	1000.00
63	150.00	750.00	70.00	350.00	70.00	350.00
64a	4.00	40.00	7.50	75.00	9.00	90.00
64f	6.00	2760.00	8.00	3680.00	11.00	5060.00
70	200.00	400.00	300.00	600.00	160.00	320.00
71	200.00	238000.00	300.00	357000.00	185.00	220150.00
72	200.00	400.00	300.00	600.00	135.00	270.00
73	175.00	7000.00	200.00	8000.00	135.00	5400.00
74	.30	150.00	.30	150.00	.25	125.00
81	.10	50.00	.15	75.00	.25	125.00
82	.25	25.00	.50	50.00	.50	50.00
83	.25	25.00	.15	15.00	.50	50.00
91	150.00	2550.00	100.00	1700.00	120.00	2040.00
92	200.00	800.00	200.00	800.00	240.00	960.00
93	150.00	750.00	150.00	750.00	120.00	600.00
94	200.00	400.00	250.00	500.00	240.00	480.00
95	200.00	200.00	200.00	200.00	170.00	170.00
120L	4.00	240.00	5.00	300.00	1.00	60.00
120E	5.00	300.00	9.00	540.00	2.00	120.00
121-	10.00	600.00	12.00	720.00	4.00	240.00
122-	4.00	240.00	4.00	240.00	.75	45.00
122L	4.00	240.00	5.00	300.00	1.00	60.00
122C	5.00	300.00	8.00	480.00	1.25	75.00
122E	5.00	300.00	9.00	540.00	1.50	90.00
125	2.00	100.00	3.00	150.00	.50	25.00
126-	3.00	300.00	4.00	400.00	.60	60.00
126L	3.00	2850.00	4.50	4275.00	.75	712.50
126C	3.00	1020.00	5.00	1700.00	.90	306.00
126G	3.00	300.00	5.50	550.00	1.05	105.00
126E	3.00	300.00	6.00	600.00	1.15	115.00
126H	3.00	300.00	6.50	650.00	1.25	125.00
126-	3.00	150.00	4.00	200.00	.90	45.00
126I	3.00	300.00	4.50	450.00	1.15	115.00
133E	10.00	600.00	9.00	540.00	1.50	90.00
138-	10.00	1100.00	6.00	660.00	.75	82.50
138L	10.00	1000.00	7.50	750.00	1.00	100.00
138C	12.00	1200.00	10.00	1000.00	1.25	125.00
138E	12.00	1200.00	12.00	1200.00	1.50	150.00
143	25.00	20000.00	25.00	20000.00	20.00	16000.00
148	8000.00	8000.00	25000.00	25000.00	15000.00	15000.00
150	150.00	3000.00	150.00	3000.00	125.00	2500.00
155	5.00	3500.00	4.00	2800.00	2.00	1400.00
164	5.00	1500.00	5.00	1500.00	6.00	1800.00
165	5.00	950.00	4.00	760.00	3.50	665.00
		949.590.00		1,244,220.00		593,191.00